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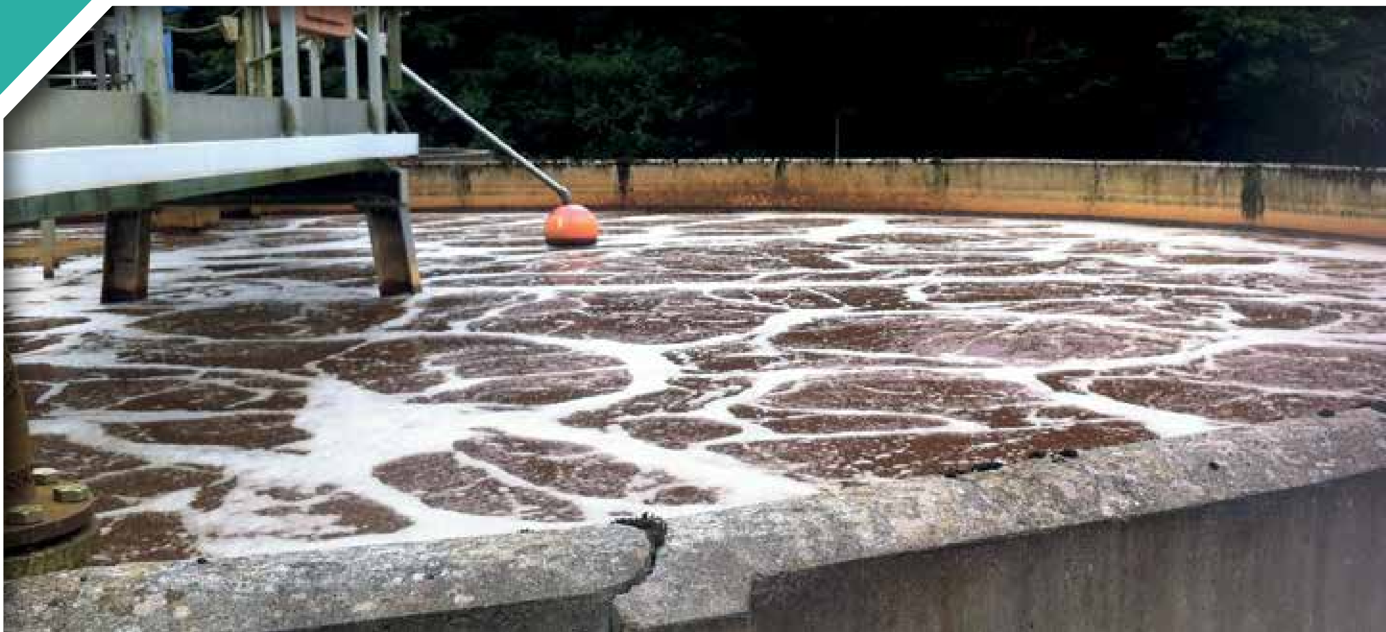
Suitability of Municipal Wastewater Treatment Plants for the Treatment of Landfill Leachate

Authors: Raymond B. Brennan, Mark G. Healy, Liam Morrison, Stephen Hynes, Daniel Norton and Eoghan Clifford



Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

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ENVIRONMENTAL PROTECTION AGENCY

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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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EPA RESEARCH PROGRAMME 2014–2020

Suitability of Municipal Wastewater Treatment Plants for the Treatment of Landfill Leachate

(2013-W-FS-13)

EPA Research Report

Prepared for the Environmental Protection Agency

by

National University of Ireland, Galway

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

In the last 30 years, there have been significant advances in waste and landfill management practices in response to European Union (EU) directives. These have led to changes in leachate composition, in the volumes of leachate produced and in its treatability. Furthermore, increasingly stringent wastewater discharge requirements mean that the co-treatment of leachate in municipal wastewater treatment plants (WWTPs) with other forms of wastewater can now be a challenge for some WWTPs. Key challenges faced by WWTP operators treating landfill leachate include high ammonium-nitrogen (NH_4-N) concentrations in leachate and the increased cost of treating wastewater to increasingly stringent standards. It is anticipated that the requirement to meet these standards will drive WWTP operators to consider their incoming load profile and the impacts on final standards that will be required.

The aims of this project were to:

- characterise the volumes and composition of leachate from landfills in Ireland;
- survey WWTP and landfill operators and conduct a technical review of how leachate is handled by WWTPs;
- examine the co-treatment of leachate with other forms of wastewater in WWTPs, specifically the impact of leachate-loading regime or rate of leachate addition on WWTP performance, and quantify the hydraulic and mass (expressed as mass nitrogen) loading of landfill leachate (as a percentage of the total influent loading rate) above which the performance of a WWTP may be inhibited; and
- analyse the costs of on-site (at landfill) and off-site treatment of landfill leachate.

Key Findings

Leachate volumes and composition

There is large temporal and spatial heterogeneity in leachate strength between landfills. Young landfill leachate represents 42% of the leachate volume, 70% of the chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5) loads, and 80% of NH_4-N leachate load in Ireland, based on data from all landfills exporting leachate during 2013. The seasonal variations in leachate production pose a risk to effective co-treatment in WWTPs, as periods of high leachate production coincide with periods of maximum hydraulic loading in WWTPs. Inhibitory compounds that can inhibit the biological treatment of wastewater, including NH_4-N, cyanide, chromium, nickel and zinc, were not found to be present at levels that would inhibit nitrification processes, provided that appropriate dilution occurs at the WWTP in the sites studied.

WWTP and landfill operators survey and review of leachate handling in Ireland

This work showed that there were few data available pertaining to leachate concentrations, volumes and treatability for landfill and to WWTP operators in Ireland.

Co-treatment in municipal wastewater treatment plants and threshold hydraulic and mass loading rates

The leachate-loading regimes at WWTPs that were examined (namely shock and drip-feed loading regimes designed by plant operators with the aim of achieving compliance) as part of this study were found to be appropriate for the effective treatment of intermediate-age landfill leachate in the WWTPs, although co-treatment may not be suitable in WWTPs with low NH_4-N and total nitrogen (TN) emission limit values (ELVs). Laboratory batch experiments showed that, with the exception of young landfill leachate, leachate loaded (at the sites examined) at volumetric rates of up to 4% of total daily influent (where the NH_4-N load was up to 50% of total WWTP NH_4-N loading) did not significantly inhibit the nitrification processes. However, young landfill leachate, loaded at volumetric rates greater than 2% (equivalent to 90% of total WWTP NH_4-N loading in the experiments), resulted in a statistically significant decrease in the effectiveness of nitrification. This study concluded that current hydraulic loading-based acceptance criteria for co-treatment of leachate at WWTPs should be reconsidered in the context of leachate NH_4-N composition, particularly for young landfill leachate.

Cost analysis

On-site treatment of landfill leachate can be effective. However, the economics of on-site versus off-site treatment of landfill leachate vary considerably and are mainly determined by site-specific factors, such as (1) proximity to a suitable discharge point for treated leachate to surface water/sewer or to a WWTP that can accept treated leachate; (2) leachate composition; and (3) level of treatment required. Introduction of a NH_4-N loading-based tariff at WWTPs would have a significant impact on the economics of on-site leachate treatment, as this would provide landfill managers with a business case to invest in on-site treatment of leachate.

Recommendations

- The current practice of co-treatment of intermediate-age landfill leachate at WWTPs is appropriate in most circumstances.
- It is recommended that, in the case of high-strength leachate being imported to a WWTP for the first time, laboratory batch experiments, as described in Chapter 4, should be conducted before leachate is imported to estimate appropriate loading rates.
- Implementation of ammonium loading-based tariffs would allow landfill operators considering the installation of on-site leachate treatment systems to make economic predictions. This would provide an economic framework for the sustainable development of leachate treatment infrastructure.
- Leachate acceptance must be planned and provision must be made for the seasonal nature of leachate loading. Leachate storage infrastructure at the landfills and WWTPs accepting leachate should be sufficient to minimise the risk of overloading WWTPs.
- Increased storage could be used as a buffer to allow leachate to be sent to WWTPs in a controlled manner. Wastewater treatment plants and landfills should design leachate storage facilities to allow for control of instantaneous leachate volumetric loading rates, as it is the loading rate over a short time period (i.e. over 24 hours), rather than the monthly/annual average, that is of greatest concern to WWTP operators.
- When completing annual environmental reports, WWTP operators should include a monthly breakdown of daily leachate volumes, loading regimes (drip-feed or shock loading) and the composition of the leachate accepted for treatment.
- Wastewater treatment plants and landfills should have overlapping measurement requirements for common contaminants. For example, total nitrogen is measured for WWTP influent, but NH_4-N is measured for leachate at the landfill. Measuring wastewater NH_4-N and landfill leachate TN would allow for accurate TN and NH_4-N loading to be determined.
- Wastewater treatment plants that are considering leachate acceptance should take account of NH_4-N and alkalinity loading rates, rather than volumetric loading rates.

1 Introduction

1.1 Overview

The European Union (EU) Waste Management Act (1996), the Landfill Directive (1999/31/EC; EU, 2001a) and subsequent legislation have driven major changes in waste management in Ireland in the last 20 years, with the number of open municipal solid waste (MSW) landfills decreasing from 95 in 1995 to four in 2014 (EPA, 2014). However, leachate management is an area of growing concern for landfill and municipal wastewater treatment plant (WWTP) operators, as increasingly stringent water quality emission limits placed on WWTPs by the Urban Wastewater Treatment Directive (91/271/EEC) and Water Framework Directive (2000/60/EC; EU, 2000) have resulted in increased costs associated with wastewater treatment. Meanwhile, increased costs, combined with concerns over leachate outlet security, are a significant challenge for landfill managers. In some cases, WWTPs have ceased accepting leachate to comply with discharge licence requirements. Figure 1.1 shows the typical landfill leachate management cycle in Ireland. The focus of this study was to provide information regarding the impact of landfill leachate on WWTP performance and to compare on-site and off-site treatment of landfill leachate.

1.2 Report Structure

Chapter 2 is a review of current literature. Chapter 3 presents a review of leachate treatment in Ireland. Chapter 4 presents the results of analyses of leachate volumes produced, contaminant concentrations in leachate and the treatability of leachates in Ireland.

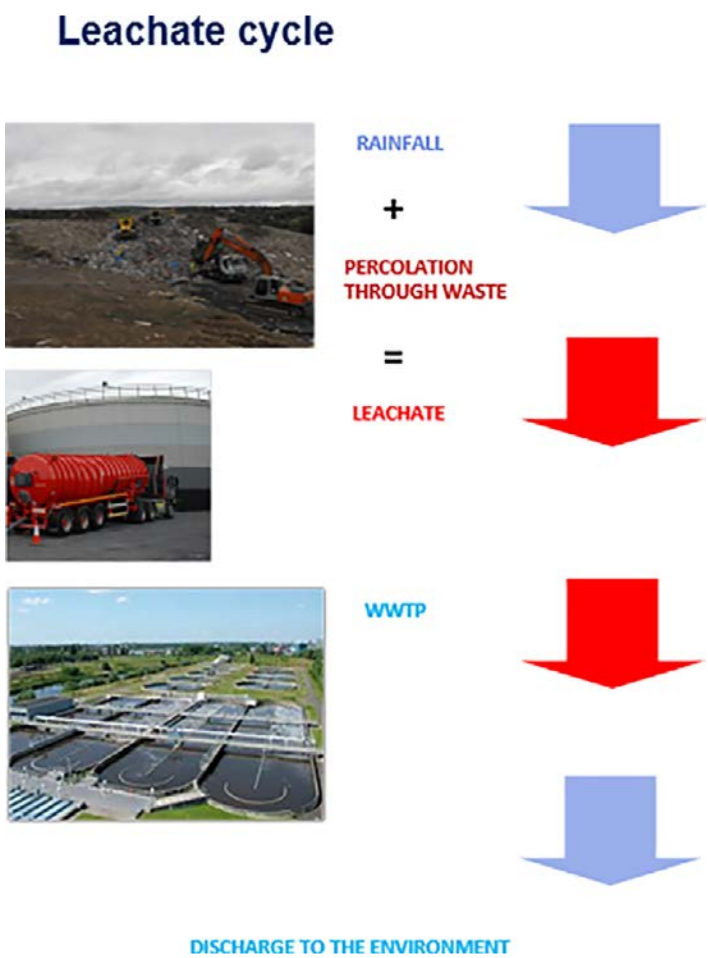

Figure 1.1. Leachate management cycle in Ireland.

Chapter 5 examines the impact of landfill leachate on WWTP performance and Chapter 6 presents the results of analyses carried out to compare the costs of on-site and off-site treatment of landfill leachate. Dissemination activities are summarised in Chapter 7, conclusions and recommendations given in Chapter 8 and guidelines for WWTP operators are outlined in Chapter 9.

1.3 Objectives

This report aimed to:

- characterise the volumes and composition of leachate from landfills in Ireland;
- survey WWTP and landfill operators;
- conduct a technical review of the treatment of leachate by WWTPs;
- examine the co-treatment of leachate in WWTPs, specifically the impact of leachate-loading regime or rate of leachate addition on WWTP performance;
- determine the maximum hydraulic and mass [expressed as mass ammonium-nitrogen (NH_4-N)] loading of young and intermediate-age landfill leachate (as a percentage of the total influent loading rate) above which the performance of a WWTP may be inhibited; and
- conduct a cost-effectiveness analysis between on-site and off-site treatment of landfill leachate.

2 Literature Review of the Treatment of Municipal Solid Waste Landfill Leachate in Ireland

2.1 Overview

The aim of this chapter is to examine the impact of EU directives on landfill management practices and landfill leachate volumes and concentrations in Ireland and to establish the context for this study. An extended version of this chapter has been published by Brennan *et al*. (2015).

2.2 Introduction

Landfill leachate is the product of water that has percolated through waste deposits that have undergone aerobic and anaerobic microbial decomposition (Chofqi *et al*., 2004; Mukherjee *et al*., 2014). Leachate composition is a function of the type of waste in the landfill (biodegradable or non-biodegradable, soluble or insoluble, organic or inorganic, liquid or solid, toxic or non-toxic waste material), landfill age, climate conditions and the hydrogeological conditions of the landfill site (Chofqi *et al*., 2004; Slack *et al*., 2005). A landfill site will produce leachate throughout its working life and also for several hundred years after it has been decommissioned (Wang, 2013). As leachate contamination of groundwater, rivers, lakes and soils has the potential to negatively affect the local environment and human population (Ağdağ and Sponza, 2005; Marshall, 2009), good management practices at landfill sites and the appropriate treatment of the leachate it produces are of paramount importance for the current and future protection of surrounding natural resources.

In 2012, 245 million tonnes of total MSW was produced in Europe (equivalent to 487 kg of MSW per person), of which the highest per capita production was in Switzerland and the lowest was in Romania (Eurostat, 2015). Of this, 240 million tonnes was treated (i.e. sent to landfill, incinerated, composted, etc.) There have been dramatic reductions in the volume of waste being sent to landfill in many European countries (for example Austria, Czech Republic, Denmark, Finland, Iceland, Ireland, Norway, Slovenia and the United Kingdom) (Figure 2.1). There has also been a reduction in the number of illegal landfills and an improvement in waste acceptance practices throughout the Member States (EC, 2007). In 2012, in all 28 EU Member States, 34% of all waste treated was sent to landfill, 42% was recycled, 4% was incinerated and 15% was composted or underwent anaerobic digestion (Eurostat, 2015). The Landfill Directive 1999/31/EC (EU, 1999a) requires that Member States reduce the amount of biodegradable municipal waste (BMW) sent to landfill by July 2016 to 35% of the total amount of BMW generated in 1995. To date Austria, Belgium, Denmark, Finland, France, Germany, Hungary, Ireland, Luxembourg, the Netherlands, Spain and Sweden have met these objectives (EPA, 2015; EEA, 2013a).

2.3 Leachate Management Practices in Europe

The Landfill Directive (1999/31/EC) (EU, 1999a), the Waste Framework Directive (2008/98/EC) (EU, 2008), the Urban Wastewater Treatment Directive (99/31/EC) (EU, 1999b) and the Water Framework Directive (2000/60/EC) (EU, 2000) are the main European regulations that directly or indirectly govern landfilling and leachate management. The Landfill Directive and the subsequent Waste Framework Directive directly impact leachate management practices, specifically leachate collection and disposal routes, which, in turn, impact leachate chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD_5), NH_4-N and total nitrogen (TN) concentrations and loading. The directives regulate the type of waste that landfills can receive and the execution of aftercare (normally 30–60 years). Recent research suggests that aftercare timelines of up to 200 years may be required, which may be reduced to 75 years where effective management practices are in place (Wang, 2013). Current EU policy proposes that all waste is managed as a resource and that landfilling is virtually eliminated by 2020 (EC, 2011; EEA, 2013b). Legislative pressures have resulted in a significant reduction in the number of operational landfills in Ireland (Figure 2.2).

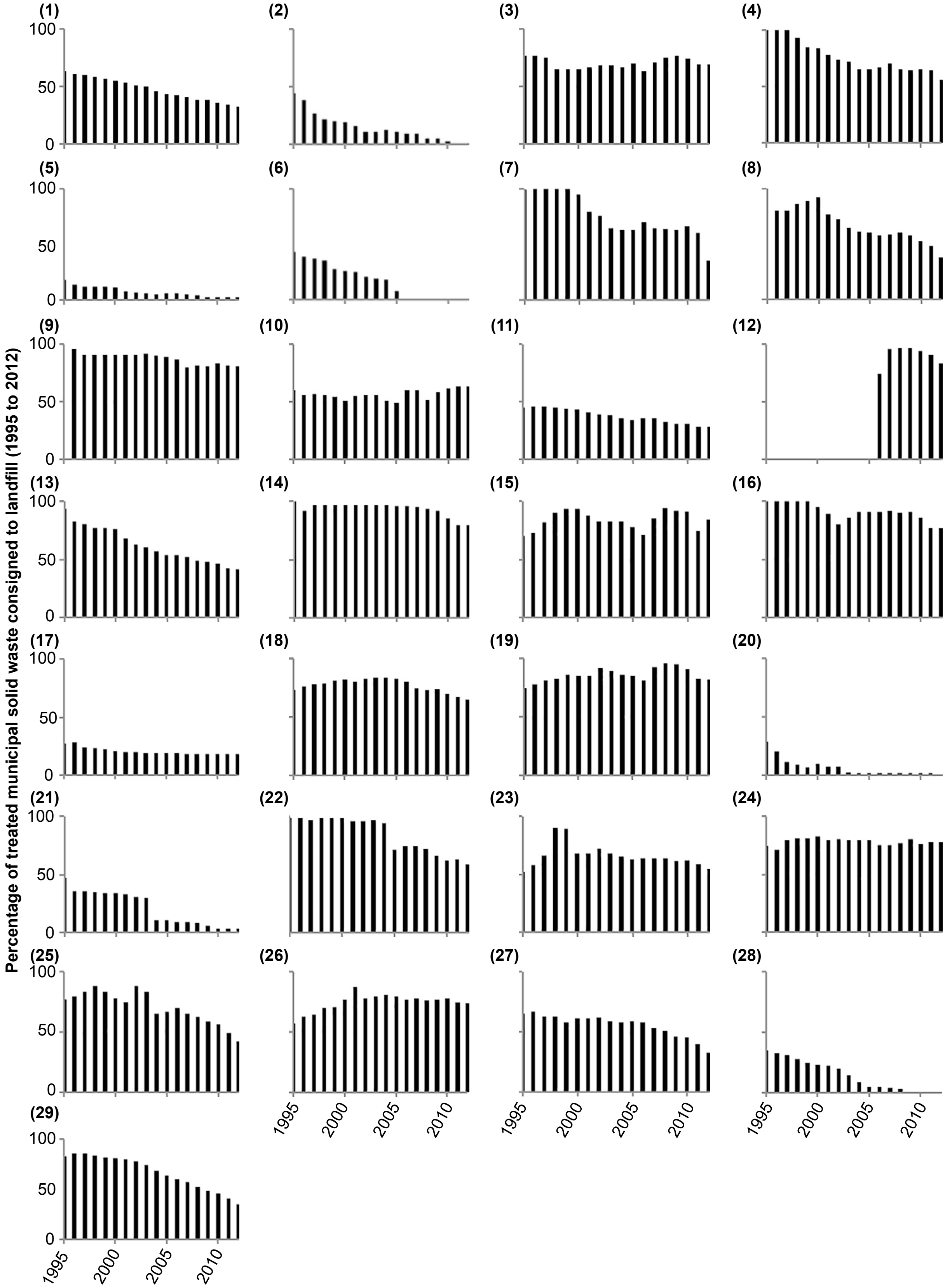

Figure 2.1. Percentage of treated municipal solid waste consigned to landfill (1995 to 2012) (Eurostat, 2015). (1) EU (27/28, post-2006) 246 Mt, (2) Belgium 5 Mt, (3) Bulgaria 3 Mt, (4) Czech Republic 3 Mt, (5) Denmark 4 Mt, (6) Germany 49 Mt, (7) Estonia 0.37 Mt, (8) Ireland 3 Mt, (9) Greece 6 Mt, (10) Spain 22 Mt, (11) France 35 Mt, (12) Croatia 2 Mt, (13) Italy 32 Mt, (14) Cyprus 0.6 Mt, (15) Latvia 0.6 Mt, (16) Lithuania 1.4 Mt, (17) Luxembourg 0.35 Mt, (18) Hungary 4 Mt, (19) Malta 0.3 Mt, (20) the Netherlands 9 Mt, (21) Austria 5 Mt, (22) Poland 12 Mt, (23) Portugal 5 Mt, (24) Romania 5 Mt, (25) Slovenia 0.7 Mt, (26) Slovakia 2 Mt, (27) Finland 3 Mt, (28) Sweden 4 Mt, (29) United Kingdom 30 Mt.
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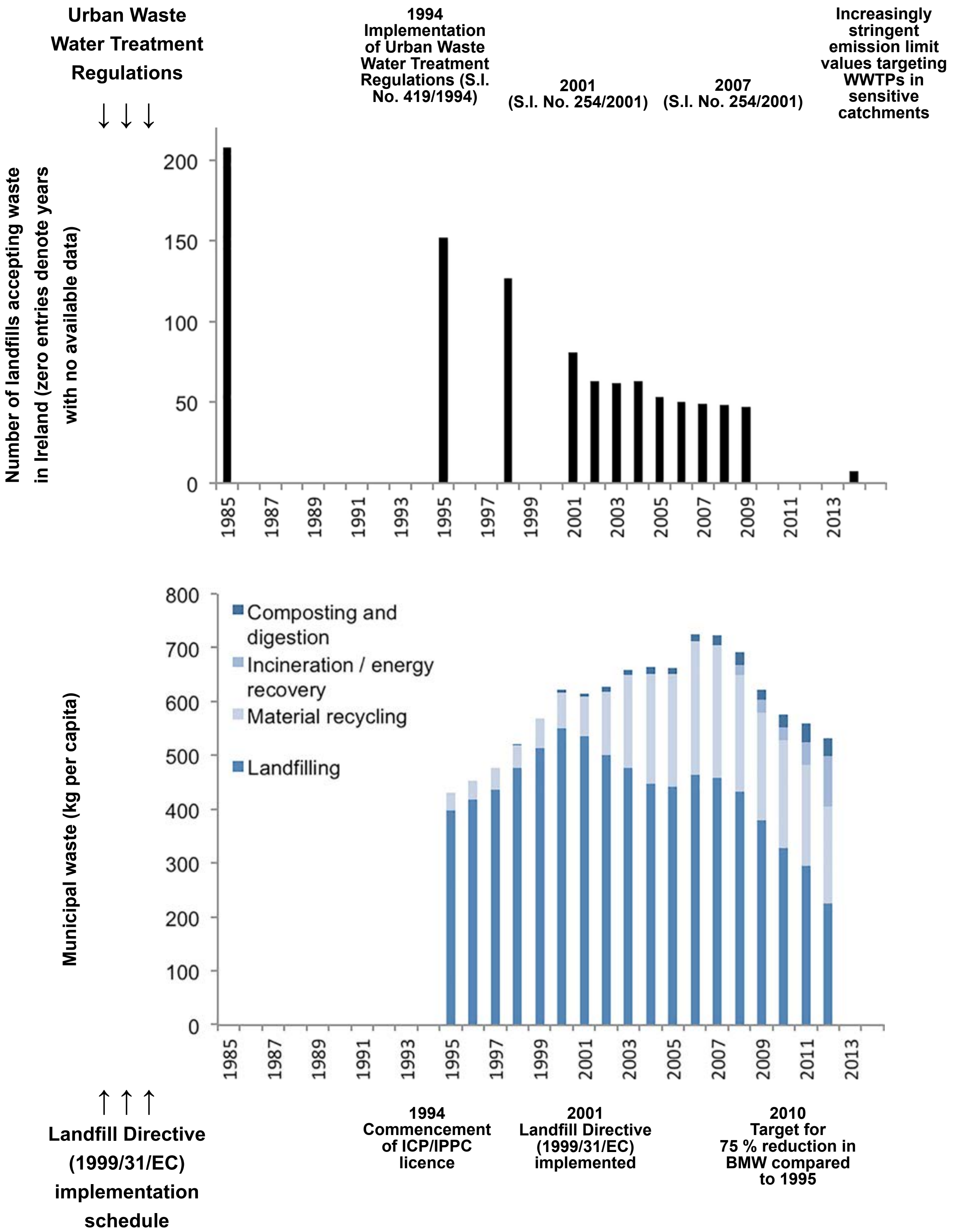

Figure 2.2. Number of landfills in Ireland accepting waste and municipal waste disposal trends plotted against time with Landfill Directive and municipal wastewater treatment regulation implementation timeline shown. ICP, International co-operative programme; IPPC, Integrated pollution prevention and control.

The Landfill Directive sets targets that (1) reduce the percentage of waste that can be consigned to landfill for each Member State; (2) decrease the quantity of BMW sent to landfill; and (3) place responsibility on landfill owners to budget for the aftercare of a landfill site for a minimum of 30 years after operation has ceased. Prior to the implementation of the Waste Management Act (Government of Ireland, 1996) and the subsequent Landfill Directive, landfilling across the EU was unregulated and poorly planned (EC, 2007). The implementation of this legislation has resulted in dramatic improvements in the way in which landfills, and specifically landfill leachate, are managed (McCarthy *et al*., 2010). There has been a decline in landfilling in recent years and leachate generation is a legacy problem; the treatment of leachate is the major management issue facing landfill operators (Zhang *et al*., 2010). Many landfills are not located close to suitable receiving waters (Knox *et al*., 2015). Therefore, the most sustainable option may be to transfer leachate to off-site WWTPs for final treatment.

In parallel to the regulations governing landfill management, the Water Framework Directive and Urban Wastewater Treatment Directive have placed tighter regulations on all discharges to waters and have resulted in stricter discharge limits being imposed on WWTPs (EU, 1999b, 2000). Where landfill leachate is treated in WWTPs, plant managers are increasingly concerned about its impact on a WWTP's ability to meet discharge limits – in particular, the removal of NH_4-N, nitrogen (N) and organic carbon (McCarthy *et al*., 2010). Throughout the EU, co-treatment of leachate with domestic sewage in WWTPs is common practice. Renou *et al*. (2008) reported that less than 21% of landfill leachate produced in France was co-treated with municipal wastewater in 2002 (this is similar to the situation in Germany, where most landfills have separate leachate treatment plants (R. Stegmann, Hamburg University of Technology, 28 August 2015, personal communication), while in other European countries, such as Poland (Kalka, 2012), the majority of leachate is co-treated with municipal wastewater in WWTPs. There is a dearth of publicly available data concerning the fate of landfill leachate and leachate treatments used on site in Europe. The main reason for this is that landfills (many of which are privately owned and operated) keep this type of information confidential, as it is commercially sensitive.

2.4 Leachate Management Practices in Ireland

In Ireland, non-compliance with NH_4-N and TN emission limits values at some WWTPs has been attributed to leachate loading and, in many instances, leachate acceptance has been discontinued in these WWTPs (EPA, 2014). There has been a 30% decrease in the number of WWTPs co-treating landfill leachate between 2010 and 2014 (EPA, 2014). Increasingly stringent WWTP emission limits will continue to challenge the sustainability of the co-treatment of leachate with municipal wastewater. The overall number of operational landfills in Ireland has decreased from approximately 200 in 1995 to 30 in 2008 (an 85% reduction) and there are approximately four landfills currently receiving waste (EPA, 2014). This decrease was primarily due to the closing of many smaller landfills as a result of the costs associated with meeting licence requirements, which proved prohibitively expensive for smaller operators (McCarthy *et al*., 2010). In addition, landfill levies have encouraged waste recovery, recycling and the export of waste (EU, 2008; Fischer *et al*., 2012; Ovens *et al*., 2013). The shift from a large number of small landfills to a smaller number of large landfills has resulted in the production of lower volumes of stronger leachate internationally (Robinson, 2005). Leachate containment and monitoring are now common practice at all licenced landfills (EPA, 2014), compared with less than one-third of landfills in 1995 (Wall *et al*., 1998). Prior to 1995, landfills were designed based on the "dilute and attenuate" principle and leachate was found to enter the environment through either seepage or overflow (Wall *et al*., 1998).

The implementation of these directives has driven significant changes in the landfilling sector in Ireland, decreasing the volume of waste sent to landfill (Figure 2.2) and decreasing the amount of BMW sent to landfill (EPA, 2015). The long-term effect of these changes on leachate composition and treatability is currently unknown. However, it is anticipated that changes in leachate composition, combined with increasingly stringent discharge requirements, will require a multi-actor approach throughout all Member States to successfully manage the legacy of landfill activities.

2.5 Municipal Solid Waste Landfill Characterisation

There are many different types of landfill leachate and MSW landfill leachate is the focus of this report. Municipal solid waste landfill leachate contains high levels of BOD_5, COD, NH_4-N, chloride (Cl), sodium (Na), potassium (K), N, boron (B), solvents, phenols, hardness and heavy metals, including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), cobalt (Co), chromium (Cr), nickel (Ni), cadmium (Cd) and lead (Pb) (Chofqi *et al*., 2004; Ağdağ and Sponza, 2005; Marzougui and Mammou, 2006). Young landfill leachate, which is generated in operational landfills or landfills that have been closed for less than five years (Renou *et al*., 2008), is highly biodegradable and exhibits COD and NH_4-N concentrations of up to 80,000 and 3100 mg L^{-1}, respectively, and BOD_5:COD ratios of up to 0.7 (Stegmann *et al*., 2005). As a result, biological treatment methods are reasonably efficient in the removal of COD, NH_4 and heavy metals (Kurniawan *et al*., 2006). Conversely, older (stabilised) leachate is less biodegradable and BOD_5:COD ratios of 0.06 are common (Choi *et al*., 2004); therefore, it is not treated as efficiently using biological methods. The age classification system employed throughout this study was the same as that used by Renou *et al*. (2008) to allow for international comparisons (Table 2.1).

2.6 Treatment of Municipal Solid Waste Landfill Leachate

To date, little work has been carried out to study the impacts of the co-treatment of landfill leachate with municipal wastewater in WWTPs (Renou *et al*., 2008) and studies have been largely limited to laboratory-scale batch experiments (Diamadopoulos *et al*., 1997; Çeçen and Aktaş, 2004). These studies have generally concluded that WWTP removal efficiency is not adversely affected, provided that the total hydraulic loading of leachate does not exceed 10% of the total municipal wastewater entering the WWTP. However, even at these volumetric loading rates (VLRs), effluent NH_4-N and TN may be significantly impacted because of their relatively high concentrations in landfill leachate (Diamadopoulos *et al*., 1997; Ferraz *et al*., 2014; Ye *et al*., 2014).

A wide range of technologies are available for the treatment of landfill leachate, including coagulation (Liu *et al*., 2012), oxidation (Chemlal *et al*., 2014), struvite precipitation (Huang *et al*., 2014), constructed wetlands (CWs) (Białowiec *et al*., 2012), membrane bioreactors (Sanguanpak *et al*., 2015) and biological treatment (Robinson *et al*., 2008; Syron *et al*., 2015). The processes underpinning these technologies have been described extensively elsewhere (Renou *et al*., 2008; Gao *et al*., 2015). There are relatively few on-site leachate treatment systems in operation in Ireland and most leachate is treated off site. The leachate treatment technologies currently in use on-site at landfills in Ireland include basic treatments, such as surface aeration of leachate lagoons and methane stripping (14% of all leachate produced) and advanced treatments, such as dedicated sequencing batch reactors (SBRs) and reverse osmosis (RO) systems (10% of all leachate produced). On-site treatment of landfill leachate is uncommon in Ireland compared with other EU countries, such as France, where 79% of leachate is treated on site (Renou *et al*., 2008). Figure 2.3 illustrates the population equivalents (PE) of WWTPs treating landfill leachate in Ireland. Approximately 5% of leachate is treated in WWTPs of up to 2000 PE, and 41% is treated in WWTPs of between 2000 and 10,000 PE.

Table 2.1. Landfill leachate classification adopted for the study (adapted from Renou *et al*., 2008)

	Landfill leachate classification		
	Young	*Intermediate*	*Old*
Age (years landfill closed)	< 5	5–10	> 10
pH	6.5	6.5–7.5	> 7.5
COD	> 10,000	4000–10,000	< 4000
BOD_5:COD ratio	> 0.3	0.1–0.3	< 0.1

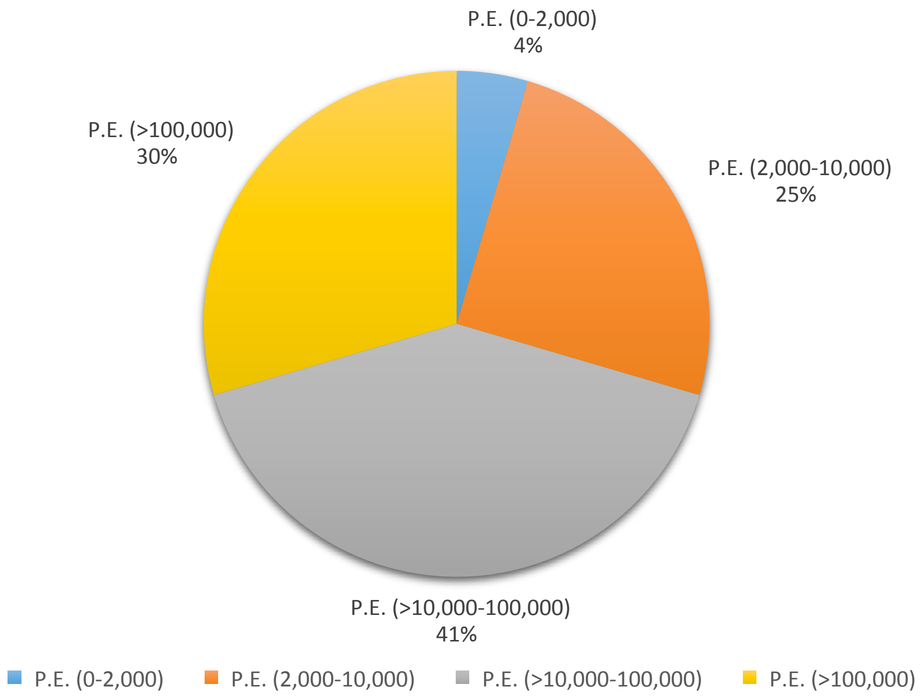

Figure 2.3. Pie chart showing the PE of WWTPs treating landfill leachate in Ireland.

In practice, landfill leachate collected in the EU is normally held in lagoons located on site, prior to transfer to WWTPs for treatment (Kalka, 2012; Kurniawan *et al*., 2010). Co-treatment of leachate with municipal wastewater has the lowest capital cost but has high operation costs, typically in the region of €25 m^{-3} of leachate, while alternative treatments have higher capital costs and lower operational costs [e.g. on-site (at landfill) SBRs discharging to sewer typically have capital costs in excess of €625,000 per treatment plant and operational costs of €1.90 m^{-3} of leachate] (Environment Agency, 2007).

2.7 Financial Considerations

Over the last 20 years, increased attention has been focused on the financial risk associated with the environmental liabilities that are associated with landfill aftercare (McCarthy *et al*., 2015). The cost of leachate treatment can be divided into operational and capital costs, and can vary significantly depending on leachate type and site-specific conditions (including age of landfill, strength of leachate, required level of treatment, volume of leachate produced, standard of construction, rainfall intensity, availability of appropriate receiving waters and proximity to sewer/WWTP).

2.8 Conclusions

This review identified the following knowledge gaps, which are discussed further in the next chapters:

1. There is limited data available pertaining to leachate concentrations, volumes and treatability for Irish MSW leachate.
2. There is a need to examine co-treatment of leachate in WWTPs, which are subject to increasingly stringent legislation in the EU, as recommendations based on out-dated studies may result in failures to achieve compliance.
3. There is a need for a cost-effectiveness analysis to compare on-site and off-site leachate treatment systems.

3 Technical Review of Leachate Volumes, Concentrations and Treatability in Ireland

3.1 Introduction

This chapter examines leachate management within Ireland and explores the impact of EU directives on landfill leachate in an Irish context. The key objectives of this study were to examine (1) how EU directives have influenced landfill leachate management and (2) to determine leachate volumes, concentrations and treatability following the implementation of the Landfill Directive. In addition, this chapter quantifies and characterises the leachate currently being treated in WWTPs.

3.2 Materials and Methods

3.2.1 Collation of existing landfill data in Ireland

Data were collated from all the 48 landfills that were collecting and exporting landfill leachate to WWTPs in Ireland. These landfills comprised 22 young, 10 intermediate-age and 16 old landfills. Data pertaining to landfill leachate management, including volumes of leachate collected for treatment, landfill leachate fate (i.e. the facility receiving the leachate), leachate treatment practices (at the landfill) and available leachate characterisation data were collated. The volume, strength and fate of all landfall leachate produced in Ireland was subsequently determined based on data obtained (1) from annual reports submitted to the Environmental Protection Agency (EPA) as part of licence requirements and (2) directly from WWTP and landfill operators. The operators of these 48 landfills were requested to provide historical records of waste acceptance, leachate production, characterisation and annual precipitation, and landfill sites were then identified for further study based on data availability. Eight of the landfills examined provided historical data. For the analysis conducted here, the landfills were labelled with their year of opening, as a number of the landfill managers requested that the name of the landfill was not published alongside the data. The case studies included young (y) and intermediate-age (i) landfills, one site with a very dilute leachate (d) and another that accepted waste that had been baled before it was sent to landfill (b).

Records detailing hydraulic loading rates and influent load (COD, BOD_5 and NH_4-N) of leachate to WWTPs were collected from 33 WWTPs in Ireland. For each WWTP, the annual influent leachate volume received was expressed as a percentage of annual WWTP influent volume and annual influent COD, BOD_5 and NH_4-N leachate loads were expressed as a percentage of annual influent COD, BOD_5 and TN loads. It should be noted that NH_4-N was expressed as a percentage of influent wastewater TN at the WWTPs, as the determination of influent NH_4-N concentrations is not a requirement at WWTPs in all cases, whereas TN analysis is not required at landfills.

3.2.2 Landfill and WWTP operator survey

Landfill and WWTP operators were surveyed to gather information concerning current leachate treatment practices. Landfill managers were asked questions focusing on factors influencing (1) leachate generation (i.e. degree of lining and capping); (2) on-site leachate management and storage capacity; (3) transport of leachate; (4) leachate treatment costs; and (5) cost-effectiveness of on-site and off-site leachate treatment systems. Wastewater treatment plant operators were asked to answer questions in the following areas: (1) the source of the landfill leachate, the volumes and concentrations (if known) treated per week; (2) the treatment regime: shock, intermittent or drip-feed loading; (3) the impact of treating leachate on final effluent concentrations (or any other intermediate concentration testing into/out of reactors); and (4) the cost effectiveness of treating landfill leachate. The surveys were first trialled on operators/managers during site visits; their feedback informed the final survey design.

3.2.3 Landfill selection and sample collection

Six of the 48 MSW landfills in Ireland, which were representative of modern engineered landfills (designed and managed since 2001), were selected for an 8-month leachate characterisation study in 2014. These comprised four young landfills and two intermediate-age landfills, which were lined (greater than 90% of landfill area lined) and capped (greater than 91% of area capped). Leachate collection points were chosen to ensure that the samples were representative of leachate exported off site to WWTPs (i.e. by pipe, manhole or tanker collection/attachment point). Samples were collected and transported to the laboratory and the samples were preserved. Analysis was then undertaken within 48 hours (APHA, 2012).

3.2.4 Analysis of wastewater and landfill leachate

All analyses were conducted in accordance with standard methods (APHA, 2012) and a summary of methodology is provided in Appendix 1. Approximately 10% of all samples were sent to an external accredited laboratory (Irish National Accreditation Board) for validation purposes. Figure 3.1 shows landfill leachate samples collected as part of this study.

3.2.5 Statistical analysis

Collated landfill data were analysed using analysis of variance (ANOVA) and data from the characterisation study were analysed using repeated measures ANOVA using the SPSS statistics package (IBM SPSS Statistics 20 Core System, Version 20). Logarithmic transformations were required for all variables to satisfy the normality assumption based on checking post-analysis residuals for normality and homogeneity of variance. A similar procedure was used for all statistical analyses throughout the study.

3.3 Results and Discussion

3.3.1 Overview of the impacts of the EU directives on landfill leachate management practices

Approximately 1.1 million m^3 of landfill leachate was collected in Ireland from MSW landfills for treatment in 2013. Although young landfills produced less than 50% of this, in 2013 they accounted for 70% of total annual leachate COD load and approximately 80% of total BOD_5 and NH_4-N loads from all landfill types (Figure 3.2). Leachate is discharged to sewer (51% by volume) or tankers for removal to WWTPs (49% by volume) for final treatment, including leachate that undergoes treatment at the landfill (EPA, 2014).

Analysis of the fate of leachate generated in Ireland during 2013 showed that the annual hydraulic loading of leachate did not exceed 4% of the total influent hydraulic load, which is the threshold recommended by the EPA (Carey *et al.*, 2000), in any of the WWTPs studied.

The hydraulic loading of leachate accounted for between 0.01% and 3.8% of WWTP influent for all WWTPs co-treating landfill leachate in Ireland. Carbon loading ratios were similar, with leachate BOD_5 loading accounting for between 0.01% and 1.8%, and COD loading accounting for between 0.01 and 5.8% (Figure 3.3). However, landfill leachate NH_4-N loading accounted for between 0.01% and 33% of influent TN loading for the WWTPs analysed in this study (Figure 3.3), which may be a concern for WWTP managers. These results indicate that hydraulic loading limits alone may not be appropriate when designing leachate

Figure 3.1. Landfill leachate samples collected as part of characterisation study (left to right: young to old landfill leachate).

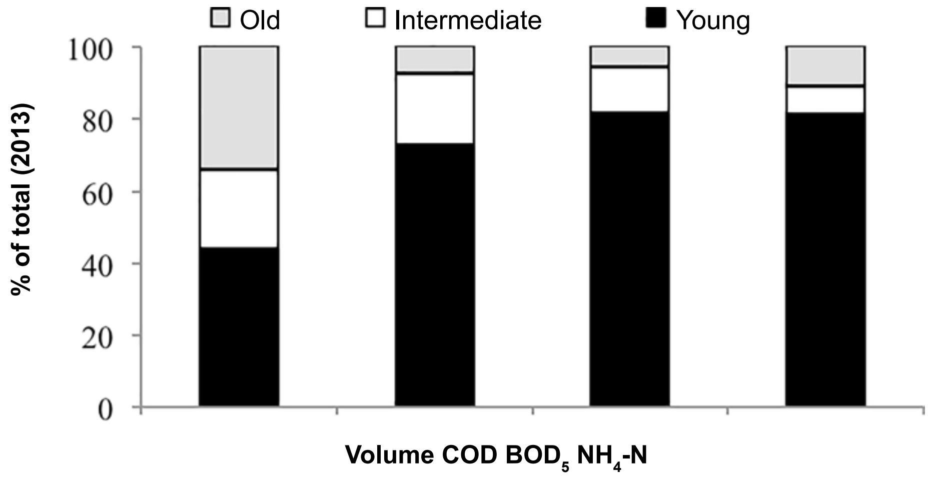

Figure 3.2 Leachate volume (m^3), COD, BOD_5 and NH_4-N load (all in kg) for young, old and intermediate landfills expressed as a percentage of total load from all landfills in 2013.

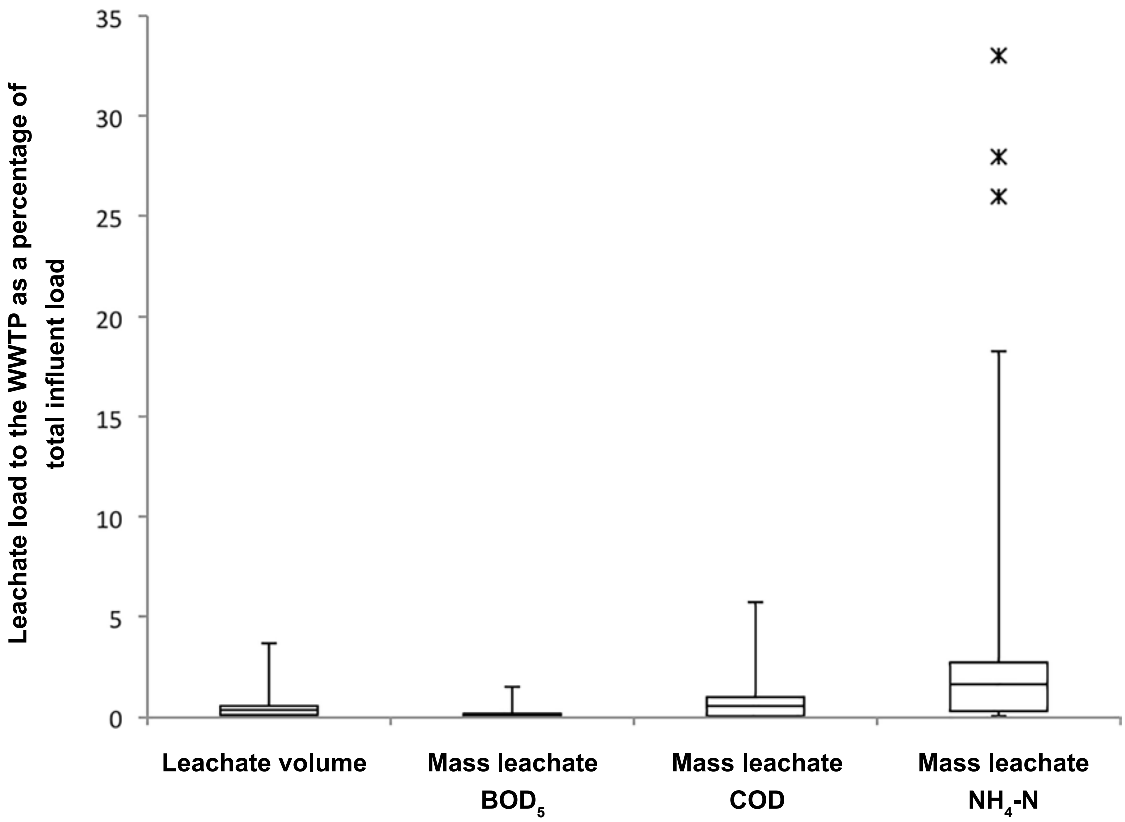

Figure 3.3. Boxplot showing leachate volume, mass BOD_5, mass COD and mass NH_4-N loading to the WWTPs influent volume as a proportion of the total influent load (x denotes outliers).

acceptance criteria. In practice, WWTP operators will consider both hydraulic and pollutant load against their available capacity, but this is not formalised. Where WWTPs are not designed to treat leachate, concerns exist regarding the impact of landfill leachate addition on the biological wastewater treatment processes and the quality of the sludge generated (Çeçen and Aktaş, 2004).

3.3.2 *Overview of collated landfill leachate composition and volumes produced in Ireland*

As expected, the mean and median concentrations of BOD_5, COD, NH_4-N and chloride were greater in leachate from young landfills compared with those from the older landfills for those examined (Figure 3.4). Median CODs were 1100 mg L^{-1}, 693 mg L^{-1} and 221 mg L^{-1} for young, intermediate and old landfills, respectively, showing a decreasing trend with increasing age category of the landfill. Similarly, BOD_5 concentrations also showed a decreasing trend (110 mg L^{-1}, 69 mg L^{-1} and 14 mg L^{-1}) and so did those of NH_4-N (352 mg L^{-1}, 218 mg L^{-1} and 98 mg L^{-1}). Young and intermediate landfill leachate BOD_5, COD, NH_4-N and chloride concentrations were not significantly different from each other, but were different from the concentrations in old landfill leachate ($P < 0.05$). These concentrations were in agreement with values reported elsewhere for intermediate (Bohdziewicz *et al.*, 2001; Frascari *et al.*, 2004) and old landfills (Robinson *et al.*, 2008). However, the concentrations for the leachate from young landfills in this study were lower than those reported for young landfill leachate elsewhere (Kjeldsen *et al.*, 2002; Renou *et al.*, 2008; Kheradmand *et al.*, 2010; Ye *et al.*, 2014).

The median BOD_5:COD ratio of young landfill leachate was significantly higher ($P < 0.05$) than intermediate landfill leachate, which in turn was significantly higher than old landfill leachate (median $0.2 > 0.1 > 0.05$, respectively) (Figure 3.5). For a typical young landfill, leachate is characterised by an acidic phase of anaerobic degradation and has a BOD_5:COD ratio of approximately 0.85, while leachates from older landfill sites can have BOD_5:COD ratios of approximately 0.06, which is similar to the median value found in this study (Chofqi *et al.*, 2004). These values were lower than expected for the leachate from the new landfills, which is likely to be a result of leachate blending of leachate from young and old cells within the landfill, and were in agreement with the results of Kjeldsen *et al*. (2002) for old and intermediate landfills. The NH_4:BOD_5 ratio of leachate from young landfills was less than that for intermediate landfill leachate, which was less than that for old landfill leachate (median $0.5 < 0.6 < 0.8$, respectively). These were not found to be significantly different.

Monthly leachate generation data, collated from 12 landfills, demonstrated seasonal variation in leachate generation in young, intermediate and old landfills. Although there was insufficient data to conduct a statistical analysis, leachate volumes were observed to

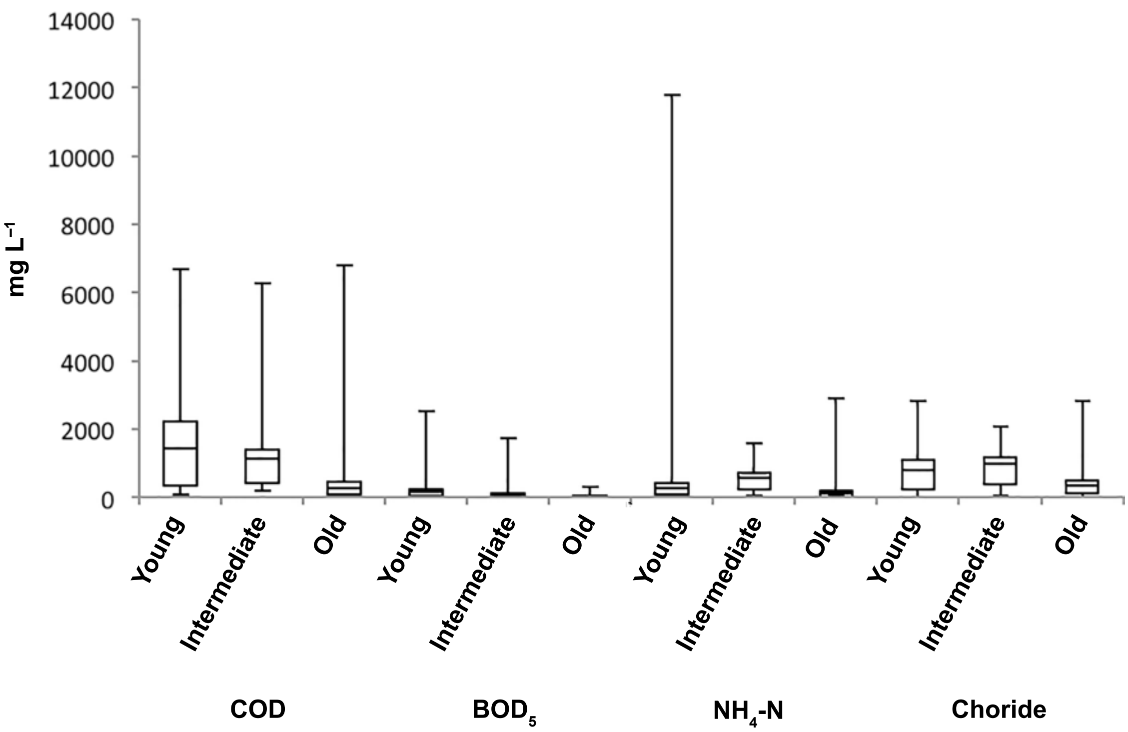

Figure 3.4. Boxplot showing leachate COD, BOD_5, NH_4-N and chloride concentrations for young, intermediate and old landfills.

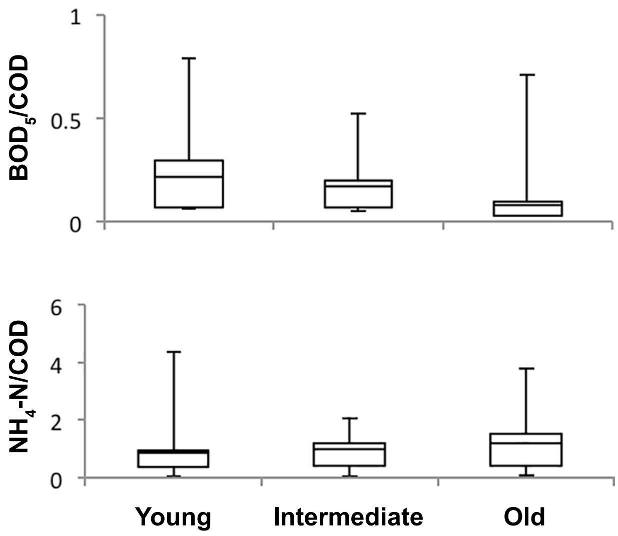

Figure 3.5. Boxplot showing the ratios of leachate COD to BOD_5 and NH_4-N to COD.

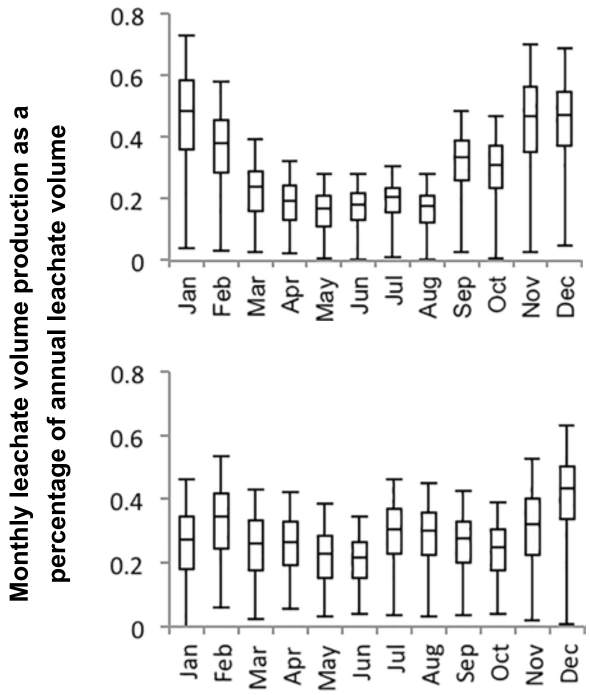

Figure 3.6. Monthly landfill leachate volume production as a percentage of annual landfill leachate volume. Top: young landfill; bottom: old landfill.

vary on average by a factor of three between summer (low) and winter (high). Figure 3.6 shows monthly leachate volume exported as a percentage of annual leachate load. Increased leachate volumes exported during winter months were attributed to precipitation on open areas at young landfills and to infiltration, and this was consistent with the findings of Robinson (2005). These results may have implications for WWTPs that receive leachate from young landfills during periods of high hydraulic loading. Unless there is adequate storage capacity at the landfill or at the WWTP to buffer high flows during extreme events, there is a risk that WWTPs could potentially be loaded with leachate during periods when they are underperforming due to high hydraulic loading.

3.3.3 Leachate characterisation

The results of the leachate characterisation study are shown in Table 3.1. The *P*-values refer to the comparison between the parameters for young and intermediate landfills. There was a strong correlation between TN and NH_4-N ($R^2 = 0.98$, $P < 0.01$). In this study, the inhibitory compounds NH_4-N, cyanide, sulphate, Cr, Ni and Zn were present in young landfill leachate at concentrations that inhibit ammonium-oxidising bacteria (Gerardi, 2002; Henze *et al*., 2002). Arsenic, Cu and Ag were present in young and intermediate landfill leachate at concentrations above inhibitory thresholds (Gerardi, 2002; Henze *et al*., 2002). The concentrations observed were lower than those reported internationally for young landfills (Kjeldsen *et al*., 2002; Renou *et al*., 2008; Kheradmand *et al*., 2010; Ye *et al*., 2014). Provided that leachate is diluted, it is unlikely that these levels would result in inhibition in co-treatment systems. However, landfill managers considering on-site biological treatment systems must be cognisant of these parameters and ensure that appropriate leachate management procedures are in place at WWTPs receiving leachate.

3.3.4 Leachate generation rates and trends in engineered landfills

Landfill operators are now much more conscious of the direct relationship between the area of active cells and leachate generation rates. Figure 3.7 shows a modern leachate storage lagoon in Ireland. There is a general decrease in the volume of leachate produced per tonne of landfill waste for landfills developed recently (Figure 3.8a). An exception to this is Case Study *1997yb* (y: young landfill; b: baled waste),

Table 3.1. Characterisation of young and intermediate landfills designed and constructed following implementation of the Landfill Directive

Parameter	Units	Young landfill leachate				Intermediate landfill leachate				Inhibitory thresholds[a]	*P*-value
		Range	Mean	Median	SD	Range	Mean	Median	SD		
pH	pH	7.6–8.5	8	8	0.28	6.8–8.4	8	7.65	7.52		<0.05
Conductivity	$\mu s\,cm^{-1}$	3089–28,430	12,664	12,615	7316	2606–10,440	5307	4502	2416		<0.001
TN	$mg\,L^{-1}$	120–4027	1352	1000	1120	120–1083	354	279	261		<0.001
Ammonia/TN		0.15–1.00	0.78	0.9	0.25	0.1–0.99	0.74	0.88	0.31		<0.05
BOD_5	$mg\,L^{-1}$	36–984	342	335	264	6–33	13	11	8		<0.001
COD	$mg\,L^{-1}$	411–7160	2656	2256	1776	190–748	361	321	141		<0.001
Alkalinity (as $CaCO_3$)	$mg\,L^{-1}$	998–9682	3521	3164	2062	10–2100	968	971	571		<0.001
Chloride	$mg\,L^{-1}$	160–2620	1218	1058	805	130–669	301	290	141		<0.001
Inhibitory compounds											
Ammonia	$mg\,L^{-1}$	130–4000	1084	772	1005	63–378	203	175	101	480	<0.001
Cyanide	$\mu g\,L^{-1}$	6–1164	252	178	278	6–81	30	31	22	100–500	<0.001
Sulphate	$mg\,L^{-1}$	7.2–1950	394	289	436	21–445	184	117	130	500	<0.05
Arsenic	$\mu g\,L^{-1}$	11–412	148	77.5	128	14.6–155	45	30.6	43	50–100	<0.001
Cadmium	$\mu g\,L^{-1}$	0.1–7.4	1	0.75	2	0.1–1.6	0.48	0.4	0.51	1000	<0.001
Chromium	$\mu g\,L^{-1}$	33–1436	446	279	408	28–284	84	55	74	1000	<0.05
Copper	$mg\,L^{-1}$	0.003–2.423	0.37	0.1325	1	0.011–0.157	0.04	0.03	0.05	0.1–0.35	<0.01
Lead	$\mu g\,L^{-1}$	0.6–1047	56	12	203	0.9–8.2	4	3.45	3	500	<0.001
Mercury	$\mu g\,L^{-1}$	0.02–1.07	0.28	0.235	0.24	0.02–2.05	0.32	0.12	1	100–250	<0.05
Nickel	$\mu g\,L^{-1}$	10–661	206	186	169	22–151	54	42	36	250–500	<0.001
Zinc	$\mu g\,L^{-1}$	10–7639	496	58	1507	10–303	83	60	86	100–300	<0.05
Silver	$\mu g\,L^{-1}$	10–2187	252	10	583	10–280	50	10	93	250	<0.05

[a]Threshold of inhibitory effect on nitrifying populations in inactivated sludge (Gerardi, 2002; Henze *et al.*, 2002).

SD, standard deviation.

Figure 3.7. Engineered leachate lagoon with cover to prevent rainwater entering the tank.

which was unique, as only pre-sorted, mechanically baled material was used at this site. For the remaining landfills examined, except *2005yd* (y: young, d: diluted with leachate collected from old unlined cells), COD, BOD_5 and NH_4-N concentrations were highest in the first 5 to 10 years after commencement of landfilling and decreased thereafter (Figure 3.8b,c,d). These findings were consistent with those of Kjeldsen *et al*. (2002) and Tatsi and Zouboulis (2002), demonstrating the difficulties faced by designers when selecting appropriate treatment technologies and making capital investment decisions. Specifically, biological systems designed to treat young landfill leachate with high biodegradability and high BOD_5:COD ratios may remove NH_4-N and COD effectively for several years while the landfill is operational; however, the same system may not effectively remove COD from older leachate, which is less biodegradable and has BOD_5:COD ratios of approximately 0.06. Renou *et al*. (2008), for example, recommended the use of packaged leachate treatment systems, which can be moved off site when they are no longer required.

The observed decrease in the volume of leachate produced per unit mass waste in the landfills examined as part of this study could be attributed to improved leachate management practices, for example improved containment and the diversion of rainwater/storm water from landfills. Reducing the volume of leachate has significantly reduced transport costs where leachate is transported by tanker from landfill to WWTP for final treatment; however, stronger leachate may require more advanced technologies to treat it effectively.

It was anticipated that the decrease in the fraction of BMW going to landfill would result in a decrease in the leachate BOD_5 and COD concentrations and a change in leachate biodegradability (determined based on BOD_5:COD ratio), as it follows that decreasing BMW in waste would decrease biodegradable carbon in leachate (Adhikari *et al*., 2014). However, it was not possible to demonstrate a change in leachate composition in response to change in the composition of BMW. This may be attributed to (1) insufficient available leachate characterisation data to compare results pre- and post-2001, which is the year the Landfill Directive was implemented and phased BMW reduction began; (2) major changes in landfill size, management and design during this period, which may also have influenced the strength of landfill leachate; (3) potential lag-time between changes in composition of the waste deposited and changes in leachate composition, which can be up to 3 years (Robinson, 2005); and (4) the effect of blending young and old landfill leachate.

3.4 WWTP and Landfill Operator Survey

The WWTP operators' survey, summarised in Table 3.2, comprises survey responses from 12 of the 30 operators invited to participate in the survey. Operators highlighted the wide variation in leachate volumes produced and accepted at WWTPs throughout the year. In addition, the landfill operator survey showed that landfill leachate storage capacities varied from 2.5 to 30 days. Of the WWTPs surveyed, 40% had

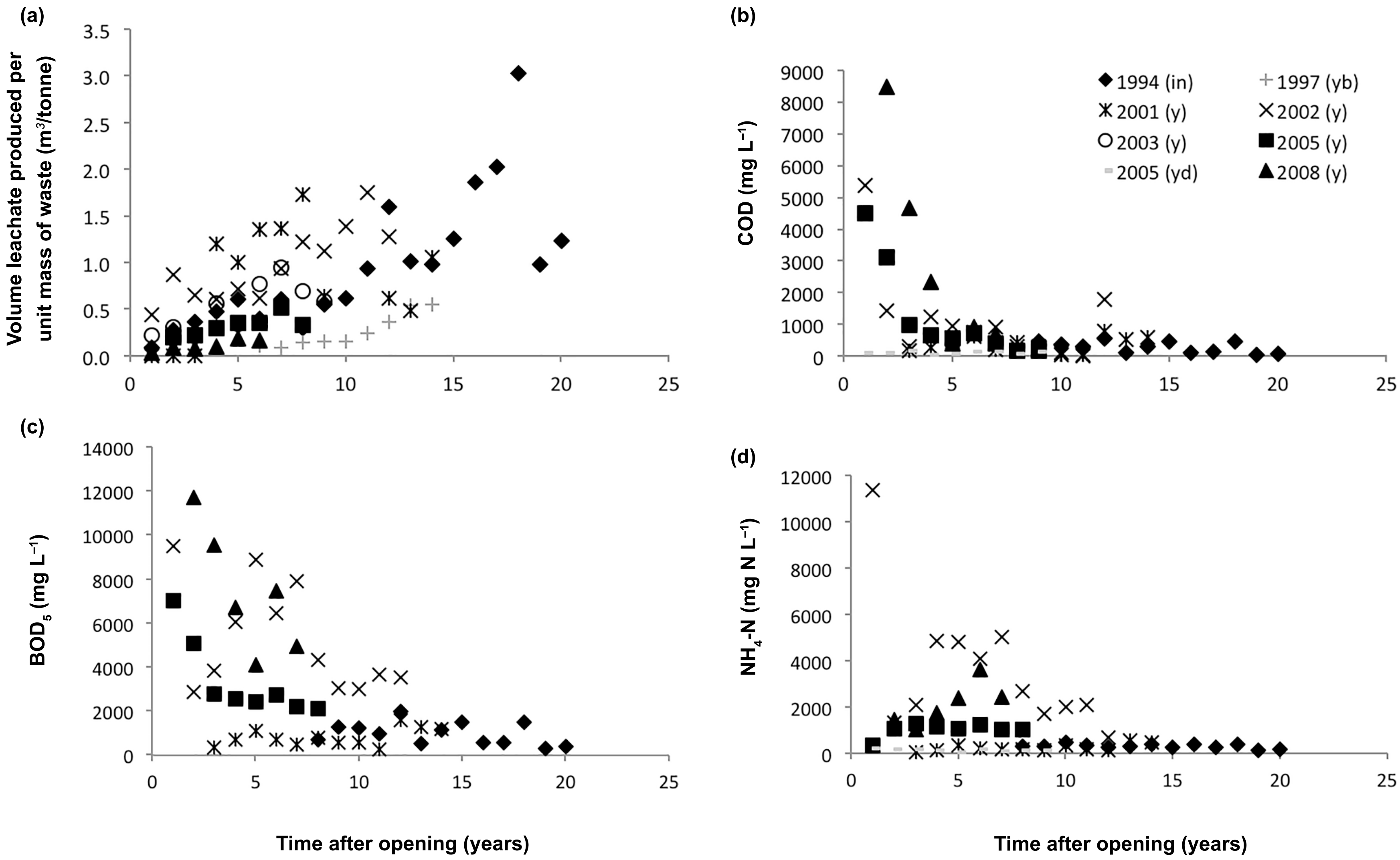

Figure 3.8. Relationship between (a) volume of leachate produced per tonne of waste sent to landfill, (b) COD, (c) BOD_5, and (d) NH_4-N concentrations and time after landfill became operational. The key indicates the year the landfill opened; y, young landfill leachate; in, intermediate landfill leachate; b, waste baled before landfilling.

Table 3.2. Select questions and responses taken from the WWTP operator survey

Question	Multiple choice answer	No. respondents	%
What are the main challenges in meeting the discharge requirements?[a]	Nitrogen	7	
	Phosphorus	3	
	Meeting maximum discharge requirements	1	
	Ammonia	2	
	Mechanical failures	3	
Actions taken/proposed to address these challenges?[a]	Improve operation and maintenance	1	
	Nothing	1	
	Proposal to construct anoxic zone	1	
	Leachate storage tank installed	2	
	On-going monitoring	1	
	Divert surplus leachate to alternate WWTP	1	
Is leachate composition known before being brought to WWTP?	Yes	2	20
	No	8	80
How is leachate imported to the WWTP?	Tanker	7	64
	Pipeline	4	36
Is there on-site storage for landfill leachate?	Yes	4	40
	No	6	60
Is there good communication between landfill and WWTP operators relating to leachate management?	Yes	8	80
	No	2	20
Does landfill leachate undergo any pre-treatment on site at WWTP?	Yes	2	18
	No	9	82
How is the leachate introduced into the WWTP?	Drip-feed (either from on-site storage, stationary tanker or pipeline)	7	64
	Shock or intermittent loading (controlled by WWTP operator)	1	9
	Shock (not controlled by WWTP operator)	1	9
	Pipeline	2	18
Where is landfill leachate added to the WWTP?	Head of works/sewer	7	78
	Start of aeration tank	2	22

[a]Respondents allowed to select more than one option.

capacity to store leachate on site. Municipal WWTP operators generally rely on leachate characterisation data supplied by the landfill operator and 20% of operators stated that leachate composition was known upon arrival at the WWTP.

The landfill operator's survey, summarised in Table 3.3, resulted in survey responses from 12 operators (out of 20 operators contacted) and identified security of disposal route, and rain and ground water infiltration as the greatest challenges faced in leachate management. The main barriers to on-site treatment of leachate that were identified were the stage of the landfill (i.e. most of leachate has already been produced), licensing issues and lack of a suitable discharge point. In 78% of cases, leachate was received at the head of the works. The most common loading regime was drip-feed loading (64%) with shock and intermittent loading being less common (9% each), with 12% of respondents not specifying leachate-loading regime. In general, plant operators were of the opinion that drip-feed systems were preferable unless the WWTP was receiving low strength leachate or leachate that was being diluted in the sewer network. The surveys facilitated interactions with project stakeholders at the start of the project and were pivotal in allowing for prompt identification of the most appropriate sites for landfill leachate characterisation, determining the impact of leachate-loading regime on WWTP performance and conducting cost-effectiveness analysis of on-site treatment versus off-site treatment.

Table 3.3. Select questions and responses from landfill operator survey

Question	Multiple choice answer	No. respondents[a]	%
Is all or part of the landfill capped?	All	5	42
	Part	7	58
Is all, part or none of the landfill lined?	All	4	37
	Part	5	45
	None	2	18
How is leachate collected at the landfill?[a]	Pumped from sump to LHL	10	67
	Controlled gravity flow to LHL	2	12
	Pumped via rising main to WWTP	1	7
	Pumped from drilled wells to LHL	1	7
	Perimeter drain to LHL	1	7
Is leachate combined with runoff from an agglomeration (e.g. waste sorting, composting, recycling areas)?	Yes	3	27
	No	8	73
Does leachate composition change throughout the year?	Yes	6	86
	No	1	14
Is leachate from different phases in the landfill collected separately?	Yes	5	45
	No	6	55
Does leachate strength determine the WWTP that the leachate is sent to?	Yes	3	43
	No	4	57
Is leachate treated on site or off site?	On-site	1	9
	Off-site	10	91
Is leachate treated on site prior to export?	Yes	3	25
	No	9	75
How is leachate transported off site?	Lorry tanker	9	75
	Sewer	1	8
	Pipeline	2	17
How is the cost of leachate treatment determined?	Per volume	8	67
	NH_4-N concentration	2	17
	COD	1	8
	BOD_5	1	8
What are the main barriers to treating leachate on site currently?[a]	Overall cost	3	14
	Operational cost of treating leachate	2	10
	Capital cost of treating leachate	3	14
	No suitable discharge point	5	23
	Licensing issues	4	19
	Sewer connection	2	10
	Treatment already in place	1	5
	Reduced leachate volume	1	5

[a]Respondents allowed to select more than one option.
LHL, leachate holding lagoon.

3.5 Environmental Policy and Management Implications for the European Union

Significant advancements in the past 30 years have reduced the impact of landfills on the environment as a result of the Landfill Directive. The Directive is widely considered to be a success and has dramatically improved waste management practices throughout the EU (EEA, 2009). However, the legacy of landfilling activities, particularly landfill leachate production, is a potential problem for landfill operators and regulators for many decades to come. The 246 Mt of waste sent to landfill in EU in 2012 had the potential to produce between 49 and 246 Mt of leachate (assuming that 1 m^3 of leachate is generated per tonne of waste sent to landfill of between 0.2 and 1.0) and the cost of leachate treatment is estimated to be between €2.10 and €25 m^{-3} of leachate (Environment Agency, 2007). The problem of leachate management may be compounded by the decrease in landfilling and reduction in revenues being generated, reducing the capacity of landfill operators to invest in treatment facilities. Future research efforts should focus on sustainable options for the treatment of high-strength leachate and data sharing must be encouraged across EU Member States to provide increased information for decision making, especially in accession countries, where lessons from Ireland may inform future policy regarding landfilling.

3.6 Conclusions

The findings of this section are as follows:

1. There is huge temporal and spatial heterogeneity in leachate strength, with young landfill leachate accounting for 42% of total leachate volume. Young landfill leachate accounts for over 70% of COD and BOD_5 load and 80% of NH_4-N leachate load (by mass) in Ireland. Therefore, treatment of high-strength leachate, which is mainly derived from young landfills, should be a priority.
2. Changes in landfill management, brought about by the EU directives, have resulted in a decrease in the volume of leachate produced per tonne of waste sent to landfill and there is a trend towards increased leachate strength (particularly for COD and BOD_5 during the initial 5 years of landfill operation). However, this study did not demonstrate the impact of decreasing BMW on leachate composition.
3. Increasingly stringent WWTP emission limits represent a significant threat to the sustainability of co-treatment of leachate with municipal wastewater and, as a consequence, the outlet security is a large risk for landfill operators.
4. The seasonal variation in leachate production poses a risk to effective co-treatment in WWTPs, as periods of high leachate production coincide with periods of maximum hydraulic loading.

4 Impact of the Treatment of Landfill Leachate in Municipal Wastewater Treatment Plants and Impacts on Effluent Ammonium Concentrations

4.1 Introduction

This chapter examines the co-treatment of leachate with municipal wastewater. It also estimates the maximum hydraulic and mass (expressed as mass nitrogen) loading of landfill leachate (as a percentage of the total influent loading rate) above which the performance of a WWTP may be inhibited. Laboratory batch experiments were used to quantify the impacts of a range of VLRs of young and intermediate landfill leachates, loaded on a volumetric basis at 0, 2, 4 and 10% (volume of landfill leachate influent as a percentage of influent municipal wastewater), on the effluent NH_4-N concentrations; the VLR is the volume of leachate treated expressed as a percentage of total WWTP influent. In addition, the effectiveness of two leachate pre-treatment technologies identified by landfill managers as having potential to be implemented during site visits (coagulation and aeration) in treating young and intermediate landfill leachate were examined using the same procedure as the laboratory batch experiments.

4.2 Materials and Methods

4.2.1 Study sites

On-site monitoring

Two activated sludge WWTPs, which were representative of WWTPs co-treating leachate in Ireland, (Sites 1 and 2) were selected for use in this study. The landfill leachates accepted at Sites 1 and 2 (intermediate) are hereafter referred to as LL1 and LL2, respectively. Landfill leachate LL1 went to Site 1, LL2 to Site 2.

Nitrification inhibition batch experiments

Batch experiments were designed to (1) determine if WWTP historical loading influenced the response to leachate addition and (2) examine young landfill leachate with higher NH_4-N concentrations than observed in LL1 and LL2. Young landfill leachate was sourced from a young landfill (LL3) and activated sludge was sourced from a WWTP that had not received landfill leachate for over 1 year (Site 3).

4.2.2 WWTP monitoring

Sites 1 and 2 were selected and monitored to determine the impact of leachate-loading regime on WWTP performance. Their operational information is summarised in Table 4.1. In 2013, Sites 1 and 2 received leachate at average VLRs of 1.2% and 2.3%, respectively. Leachate-loading regimes examined during the study were (1) drip-feed loading; (2) no leachate addition; and (3) shock loading (i.e. relatively large leachate volumes added to the WWTP in a brief pulse). Drip-feed and no leachate scenarios were examined at Site 1 and shock loading was examined at both Sites 1 and 2 (Table 4.1). Refrigerated automatic wastewater samplers (Aqua Cell, UK) were used to collect grab samples at 8-hour intervals at the head of the works prior to primary settlement and at effluent discharge points (effluent wastewater samples) of Sites 1 and 2. Influent and effluent flows were recorded using on-site flow recording equipment. For operational reasons, it was not practical to monitor each loading regime for a time period longer than the sludge age of the WWTP and this must be taken into account when interpreting differences between leachate-loading regimes. Neither of the WWTPs examined were designed/operated for denitrification to occur.

4.2.3 Nitrification inhibition batch experiments

Laboratory batch experiments, conducted to supplement the results of the WWTP study, examined the impact of various landfill leachates on NH_4-N removal in controlled experiments. Landfill leachates LL1 and LL3 were added to activated sludge taken from aeration tanks at Sites 1 and 3 at VLRs [volume

Table 4.1. Study site wastewater treatment plant operational information (data from 2013)

WWTP identifier	Units	Site 1	Site 2
Design PE	PE	5000	25,000
Operating PE		2000	19,000
Leachate treated at WWTP		Leachate Site 1 (LL1)	Leachate Site 2 (LL2)
Transportation method		Tanker	Sewer
Leachate-loading regimes examined during the study		Drip-feed	Shock-high
		No leachate	Shock-low
		Shock	
Leachate entry point		Aeration tank	Sewer
Leachate pre-treatment		None	None
Annual volume leachate accepted	$m^3 yr^{-1}$	7302	47,744

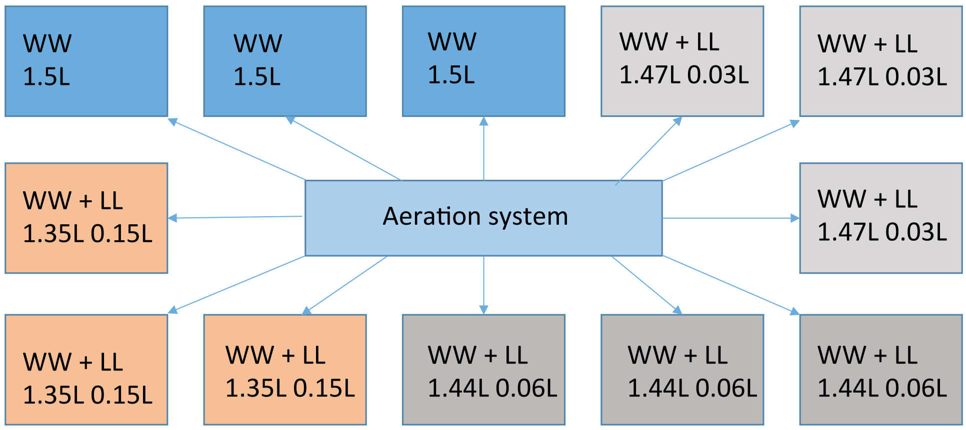

Figure 4.1. Experiment design of batch experiments.

of landfill leachate/volume mixed liquor suspended solids (MLSS) sample] of 0, 2, 4 and 10% ($n=3$ for each experiment) as shown in Figure 4.1. Landfill leachate and activated sludge were collected, transported to the laboratory and stored at 4°C. Batch experiments were conducted within 12 hours of sample collection. Experiments were conducted in triplicate using 2L-capacity beakers in a cold room with a controlled temperature of 10°C, which is similar to mean air temperatures observed in Ireland (Met Éireann, 2015). Samples were added to the beakers and aeration commenced immediately using an air-stone placed at the base of each beaker. Beakers were constantly aerated with an air flow sufficient to ensure suspension of solids throughout the experiment. pH and dissolved oxygen (DO) were measured and samples withdrawn from the beakers (2mL) to be tested for alkalinity, NH_4-N and nitrate nitrogen (NO_3-N) analysis at $t=0.125$, 0.25, 0.5, 1, 2, 4, 6, 24 hours after the start of the experiment. After 48 hours, aeration was ceased, and filtered and unfiltered samples were taken for COD and CODs (soluble faction of COD) analysis.

4.2.4 Data analysis

Daily VLR was determined by expressing the daily volume of leachate treated as a percentage of the daily influent treated at the WWTP. The instantaneous volumetric loading rate (VLR_i) was determined by expressing the volume of leachate treated as a percentage of the volume of influent treated during the time the leachate was discharged to the WWTP/ sewer from the tanker or on-site storage tank. Daily leachate BOD_5, COD and NH_4-N mass loads were also expressed as a percentage of daily WWTP influent BOD_5, COD and NH_4-N mass loads.

4.3 Results

4.3.1 Landfill leachate characterisation

The range and mean concentrations of pH, conductivity, NH_4-N, TN, BOD_5, COD, BOD_5:COD ratio, alkalinity, chloride, sulphate and suspended solids (SSs) in landfill leachate accepted at the two study sites are shown in Table 4.2. Concentrations of inhibiting compounds, such as NH_4-N (Table 4.3), As and Cu (Table 4.4), were not above typical inhibitory thresholds (480 mg L^{-1}, 0.05–0.1 mg L^{-1} and 0.1–0.35 mg L^{-1}, respectively) for nitrifying populations in inactivated sludge (Gerardi, 2002; Henze *et al.*, 2002).

4.3.2 WWTP monitoring

Site 1

Influent volume, COD, BOD_5, total inorganic carbon measured after filtration through a 0.45 μm filter (TIC_f), total organic carbon after filtration through a 0.45 μm filter (TOC_f), total nitrogen after filtration through a 0.45 μm filter (TN_f) and NH_4-N daily mass loads and concentrations did not differ significantly between the three loading regimes (drip-feed, no leachate and shock loading; $P < 0.05$) (Table 4.5). There were no significant differences between influent and effluent As, Cd, Cr, Cu, Pb, Hg, and Ni concentrations (Table 4.4). Daily carbon loading rates were similar to VLRs (Figure 4.2), with average daily leachate loading accounting for less than 0.1% and 2% of total BOD_5 and COD loads to the WWTP throughout the study, respectively. Average daily TN and NH_4-N loading accounted for a maximum of 9% and 8% of TN and NH_4-N daily loads to the WWTP, respectively. The VLR_i results indicated that the leachate-loading regime had a significant impact on mass loading at WWTP when co-treating leachate. The VLR_i was unchanged during the drip-feed phase, but increased to 16% during the shock loading phase (Figure 4.2), whereas instantaneous TN and NH_4-N loading increased from 9% and 8% to 40% and 39%, respectively. These results show that, even at VLR lower than 4%, the mass loading can be over 10 times higher and potentially lead to challenges in meeting discharge requirements (or cause operational issues for the WWTP).

The leachate-loading regime at Site 1 did not have a statistically significant impact ($P < 0.05$) on percentage removals of BOD_5, COD, TIC_f, TOC_f, TN_f, or NH_4-N (Table 4.3) or effluent concentrations (Figure 4.3) when comparison was made between effluent from drip-feed, no leachate and shock loading regimes. Although percentage removals were not significantly affected, it is likely that mass removals were increased, as varying loading regimes had different mass influents.

Site 2

High and low shock loading regimes were similar in that there was uncontrolled shock flow once the pump

Table 4.2. Study site landfill leachate characterisation

		Leachate tankered to Site 1 (LL1)			Leachate pumped via pipeline to Site 2 (LL2)		
		Range	Mean	SD	Range	Mean	SD
pH	pH	6.8–7.8	7.3	1	7.8–8	8	0.12
Conductivity	μs cm^{-1}	6840–6870	6855	21	3117–4578	3803	735
NH_4-N	mg L^{-1}	245–378	311	67	120–246	183	89
Total nitrogen	mg L^{-1}	279–429	351	75	130–380	253	130
BOD_5	mg L^{-1}	8–20	14	6	100–700	396	300
COD	mg L^{-1}	274–420	361	77	698–2190	1362	759
BOD_5:COD ratio		0.03–0.05	0.04	0.01	0.14–0.32	0.26	0.1
Alkalinity	mg L^{-1}	10–1083	547	759	1306–1918	1554	322
Chloride	mg L^{-1}	130–201	163	36	160–371	290	114
Sulphate	mg L^{-1}	109–320	210	106	7.2–93	43	45
SS	mg L^{-1}	12–89	44	40	45–126	79	42

SD, standard deviation.

Table 4.3. Wastewater treatment plant influent and effluent concentrations at each study site WWTP

WWTP	Regime	BOD_5 ($mg L^{-1}$)		COD ($mg L^{-1}$)		TIC_f ($mg L^{-1}$)		TOC_f ($mg L^{-1}$)		TN_f ($mg L^{-1}$)		NH_4-N ($mg L^{-1}$)	
		Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
Site 1	D	262	0	405	41	20	9	26	10.369	20	21	17	1.7
	N	186	3	361	38	16	12	19	11.484	20	13	19	1.07
	S	274	3	422	31	34	14	29	12	23	22	20	1.04
Site 2	S_H	289	21	692	63	49	22	67	17	36	28	31	4.3
	S_L	181	12	658	46	49	13	54	12	36	25	32	0.65

D, drip-feed loading; eff, effluent; inf, influent; N, no leachate; S, shock loading; S_H, high shock loading; S_L, low shock loading.

Table 4.4. Metal concentrations in WWTP influent, effluent and landfill leachate accepted at each study site WWTP

Parameter		Cadmium[a] ($mg L^{-1}$)	Lead[a] ($mg L^{-1}$)	Mercury[a] ($mg L^{-1}$)	Nickel[a] ($mg L^{-1}$)	Arsenic ($mg L^{-1}$)	Chromium ($mg L^{-1}$)	Copper ($mg L^{-1}$)
Units								
Site 1	Influent (before leachate added to aeration tank)	0.3[b] (0)	1.7[b] (1.09)	0.06[b] (0)	6.3[b] (2.9)	1.06[b] (0.13)	5.7[b] (4.6)	0.01[b] (0.01)
	Effluent	0.3[b] (0)	1.1[b] (0.51)	0.11[b] (0.17)	5.6[b] (1.47)	1 (0)[b]	4.1[b] (1.02)	0.01[b] (0)
	Leachate at point of entry to sewer	0.6[b] (0)	3.17 (1)	0.12a(0)	57(5)	33 (1)	93 (23)	0.03 (0)
Site 2	Influent (including leachate that was in sewer)	0.3[b] (0)	4.41 (2.15)	0.08[b] (0.03)	5.7(1.85)	1.55[b] (1.14)	6.2[b] (5.7)	0.12 (0.05)
	Effluent	0.3[b] (0)	0.91[b] (0.03)	0.06[b] (0)	4.57(0.29)	1.01[b] (0.03)	4.1[b] (2.8)	0.04[b] (0.03)
	Leachate at point of entry to WWTP	0.23[b] (0.1)	2.25[b] (1.85)	0.06(0.03)	31(16.5)	22 (10.03)	63 (29)	0.02[b] (0.01)
	Nitrification inhibiting value[c]	1	0.5	0.1	0.5	0.05–0.1	1	0.1–0.35

Standard deviation in parenthesis.

[a]parameter concentrations that are not significantly different from each other when compared between leachates (*P* < 0.05).

[b]metals on the priority substances list (EU, 2008).

[c]Nitrification inhibiting values for each parameter taken from Hanmer *et al.* (1983).

Table 4.5. Wastewater treatment plant influent and effluent daily loads and percentage removal efficiency at each study site WWTP

WWTP	Regime	Average volume	BOD_5 (kg d^{-1})			COD (kg d^{-1})			TIC_f (kg d^{-1})			TOC_f (kg d^{-1})			TN_f (kg d^{-1})			NH_4-N (kg d^{-1})		NH_4-N_{eff} TN_{inf}
		$m^3 d^{-1}$	Inf	Eff	%	Inf	Eff	%	Inf	Eff	%	Inf	Eff	%	Inf	Eff	%	Inf	Eff	%
Site 1	D	2040	319	2	99	487	68	91	27	13	34	32	10	55	26	42	–2	24	2	91
	N	2470	512	9	97	905	97	88	37	26	16	46	11	47	49	30	39	44	3	96
	S	2400	600	7	99	803	75	90	80	39	55	56	12	62	46	49	8	40	3	95
Site 2	S_H	6450	1926	146	91	3742	394	88	324	144	52	436	106	75	238	174	20	200	30	87
	S_L	6210	1069	71	94	4082	270	93	294	79	69	323	72	77	217	149	29	191	4	98

D, drip-feed loading; eff, effluent; inf, influent; N, no leachate; S, shock loading; S_H, high shock loading; S_L, low shock loading.

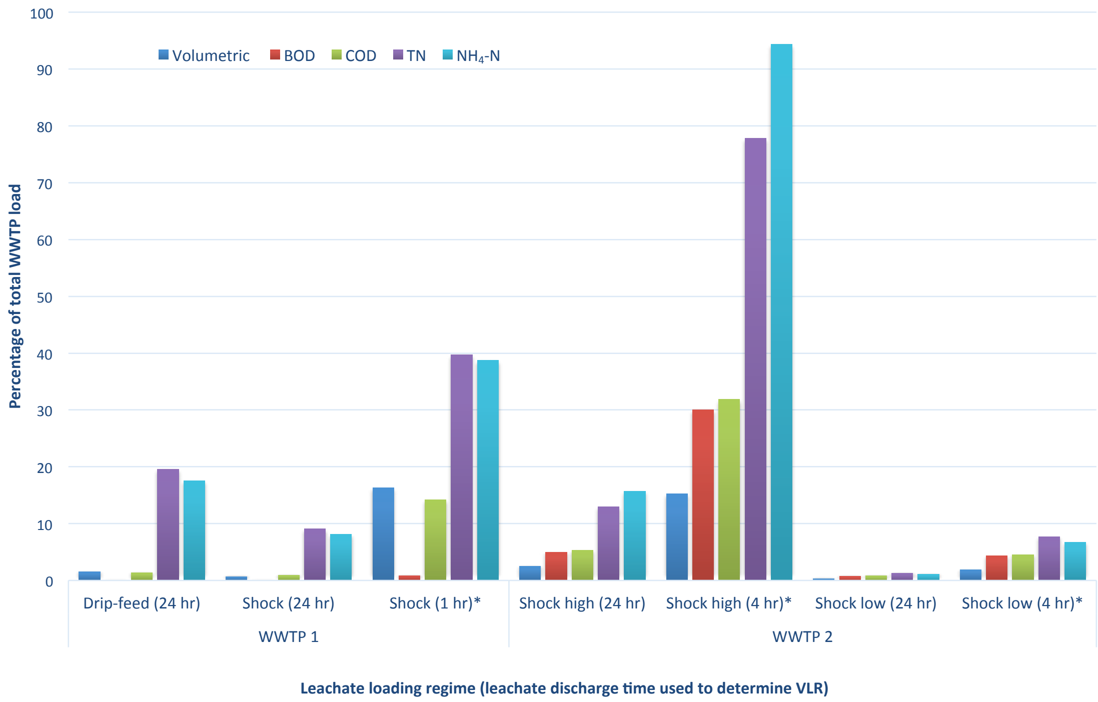

Figure 4.2. Bar chart showing leachate daily and instantaneous VLR, BOD_5, COD, TN and NH_4-N mass loads as a percentage of WWTP influent mass.

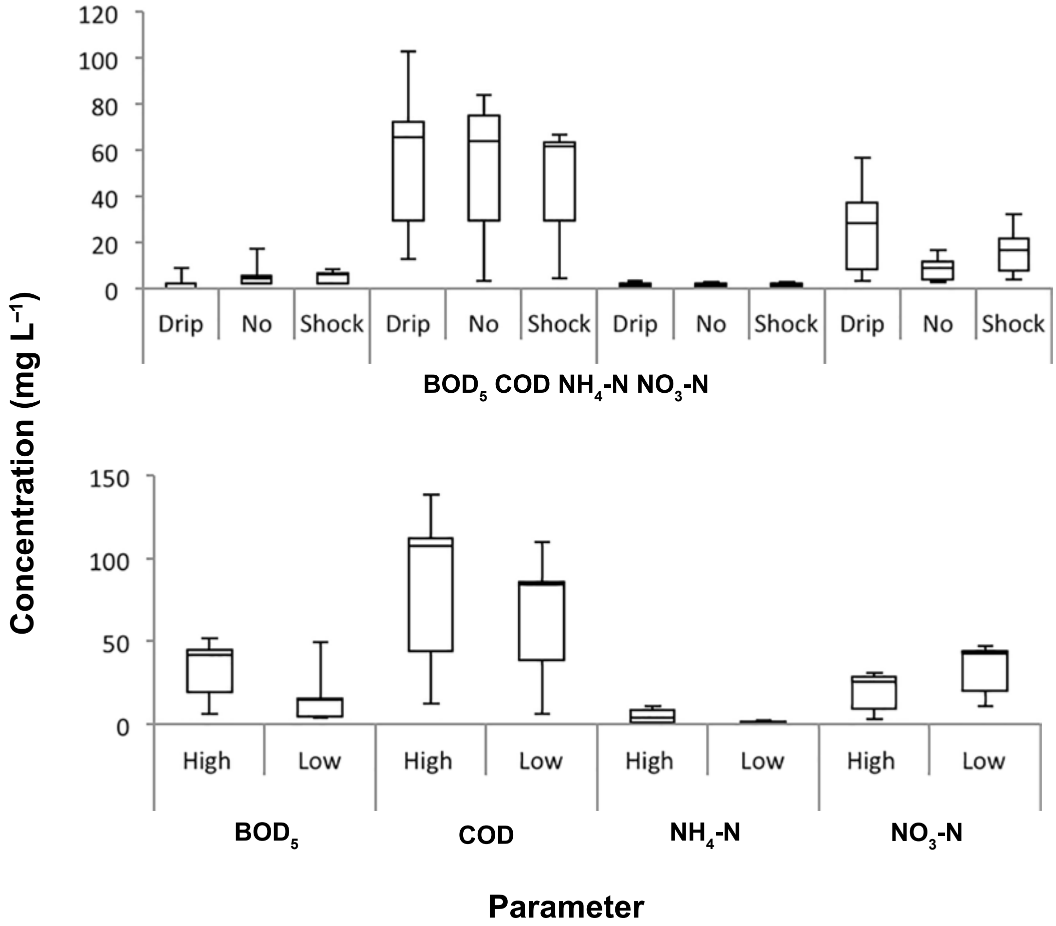

Figure 4.3. Boxplot showing the characteristics of WWTP effluent from the two study sites (top: site 1; bottom: site 2).

activated, although with a significantly higher VLR for the high shock regime (2.5%) compared with 0.3% for the low shock regime (Figure 4.2). The equivalent daily BOD_5 mass loading ratios decreased from 5% to 0.7%, COD from 5.3% to 0.8%, and NH_4-N from 16% to 1.1% when the leachate-loading regime was reduced from a high to a low loading rate. The VLR_i decreased from 15.2 to 1.9% during the high and low leachate-loading phases (Figure 4.2). The leachate-loading regime at Site 2 did not significantly impact the COD and BOD_5 percentage removals when comparisons were made between the effluent from each leachate-loading regime (Table 4.3). However, TIC_f ($P<0.05$), TOC_f ($P<0.05$) and NH_4-N ($P<0.001$) percentage mass removals increased significantly when the leachate-loading regime was reduced from a high to a low loading rate. Decreasing leachate loading resulted in decreased effluent NH_4-N concentrations, with mean NH_4-N concentrations decreasing from 4.0 mg L^{-1} during the high loading period to 0.65 mg L^{-1} during the low loading period ($P<0.001$) (Figure 4.2). There were no significant differences between influent and effluent As, Cd, Cr, Cu, and Ni concentrations, although effluent Pb and Hg concentrations were significantly lower, indicating that these were removed in the WWTP (Table 4.5).

Laboratory batch experiments

The initial COD, NH_4-N, total oxidised nitrogen (TON), alkalinity, MLSS and volatile suspended solids (VSS) concentrations for activated sludge and leachate used in laboratory batch experiments are shown in Table 4.6. Wastewater activated sludge samples taken from aeration tanks at Sites 1 and 3 were similar, except for alkalinity and MLSS concentrations. Table 4.7 shows

Table 4.6. Beaker experiment leachate and activated sludge characterisation at time of collection

Experiment	COD	NH_4-N	Alkalinity	TON	MLSS	VSS
Activated sludge from Site 1	3664	4.76	62.5	0.63	3265	2585
Activated sludge from Site 3	3232	5.93	34	6.94	1475	1075
Leachate from landfill 1 (LL1)	1236	134	700	1.03	135	60
Leachate from landfill 3 (LL3)	11,373	2800	7820	1.1	360	195

All measurements shown in mg L^{-1}.

Table 4.7. Beaker experiment soluble and total COD, pH and DO

	VLR	COD (mg L^{-1})	pH		Dissolved oxygen (mg L^{-1})	
	%	48 hours	0.125 hours	48 hours	0.125 hours	48 hours
Activated sludge from Site 1 and LL1	0	3750 (1490)	6.3 (0)	5.3 (0)	9 (0.4)	9.9 (0.2)
	2	3250 (1070)	6.5 (0.2)	5.5 (0)	9.1 (0.2)	10 (0.6)
	4	2660 (2090)	6.8 (0.1)	5.3 (0.1)	8.6 (0.2)	9.8 (0.2)
	10	4630 (695)	7.4 (0)	5.3 (0.1)	7.5 (1.5)	9.7 (0.2)
Activated sludge from Site 1 and LL3	0	2020 (2290)	6 (0.2)	5.6 (0.2)	8.3 (1.2)	11.5 (0.4)
	2	2430 (1780)	7.1 (0.2)	5.5 (0.7)	8.6 (1.3)	11.2 (0.3)
	4	2570 (977)	7.6 (0.2)	6.8 (0.7)	9.5 (0.2)	10.4 (0.4)
	10	2580 (1960)	8.1 (0.1)	9.4 (0.1)	9 (1)	10.2 (1.5)
Activated sludge from Site 3 and LL1	0	3910 (1340)	8 (0.2)	8 (0)	7.9 (0.1)	2.5 (0.3)
	2	4000 (2320)	7.8 (0.2)	8 (0.1)	8.1 (0.2)	1.9 (0)
	4	3850 (2160)	7.5 (0.1)	8 (0.1)	6 (1)	1.6 (0.3)
	10	5910 (411)	7.3 (0.3)	7.8 (0.2)	9.5 (15.2)	1.5 (0.1)
Activated sludge from Site 3 and LL3	0	5040 (2010)	7 (0.1)	6.8 (0.2)	4.2 (0.7)	8.3 (1.7)
	2	4610 (994)	7.6 (0.1)	6.7 (0.3)	3 (2)	8.5 (0.8)
	4	2360 (1560)	7.9 (0.2)	6.9 (0.7)	4.1 (0.6)	8.1 (1.7)
	10	6360 (928)	8.4 (0.2)	8.8 (0.1)	5.8 (2.2)	8.9 (0.6)

Standard deviation in parenthesis.

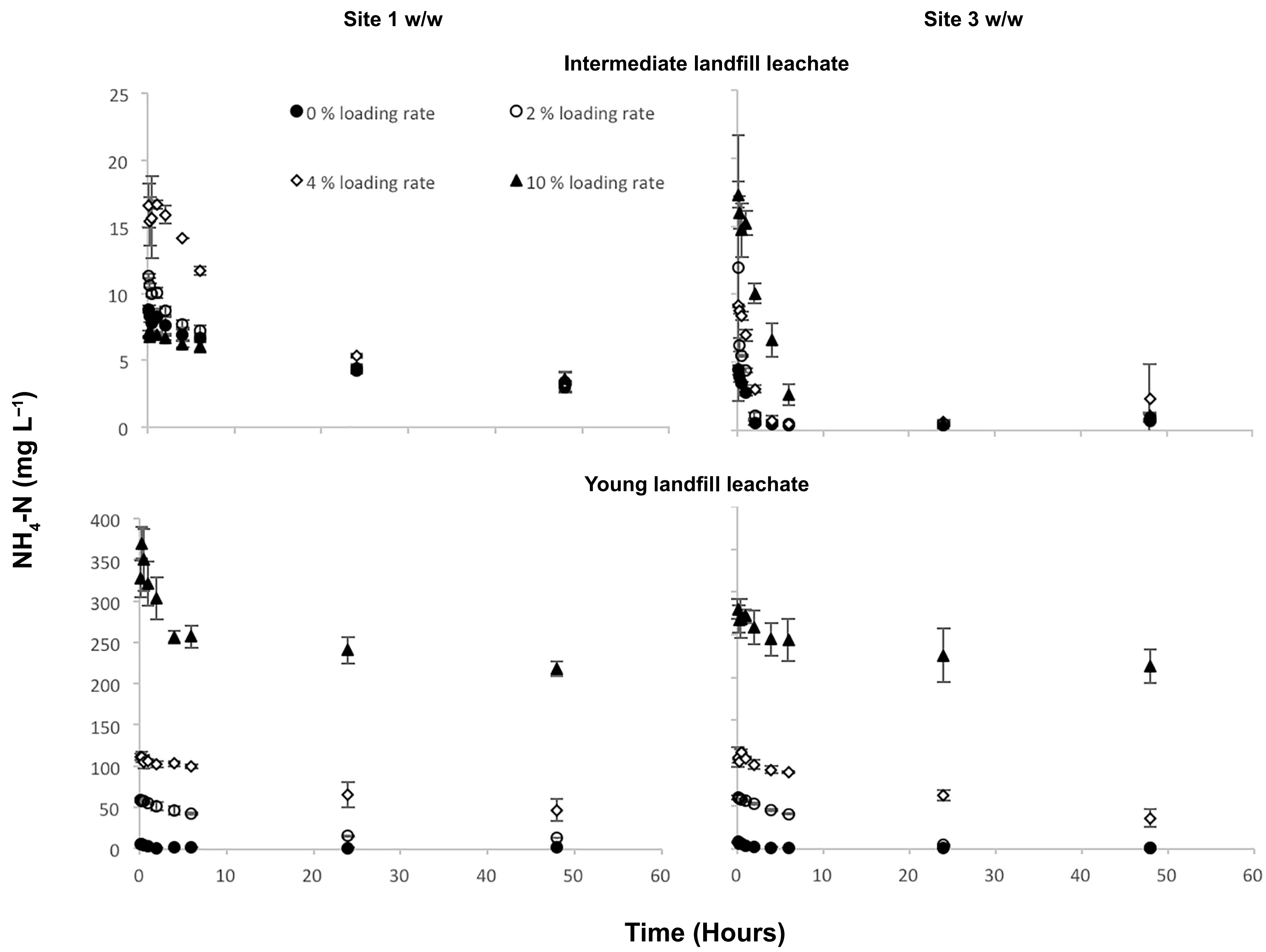

Figure 4.4. Nitrification inhibition experiment NH_4-N trends at 0, 2, 4 and 10% leachate-loading rates (error bars denote standard deviation). w/w, weight per weight.

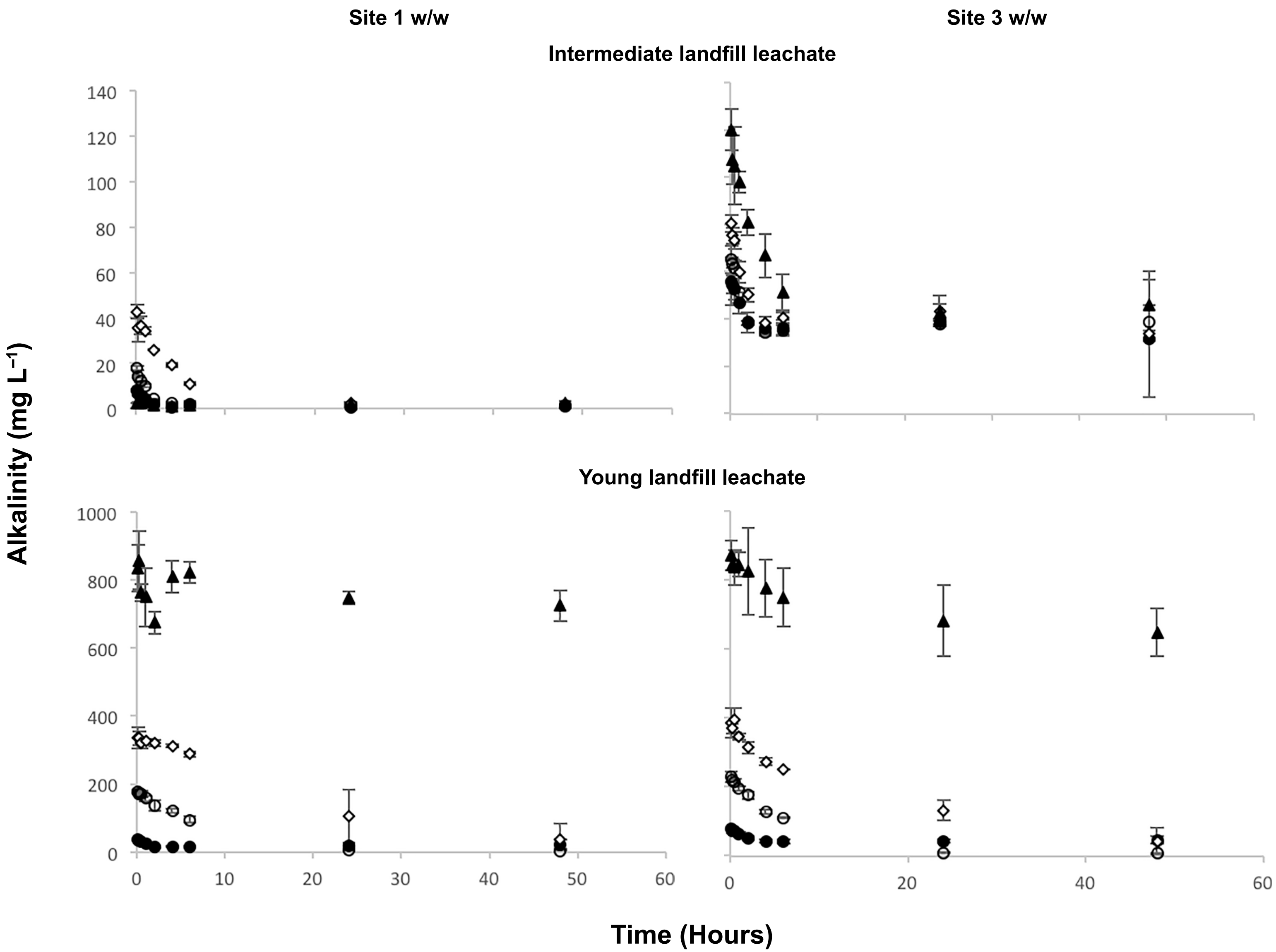

Figure 4.5. Nitrification inhibition experiment alkalinity trends at 0, 2, 4 and 10% leachate-loading rates (error bars denote standard deviation).

the results for wastewater/wastewater and leachate mixture COD (at $t=48$ hours), pH and DO (at $t=0.125$ and $t=48$ hours).

NH_4-N concentrations and alkalinity were observed to decrease relatively steadily until approximately 6 hours after the experiment started (Figures 4.4 and 4.5). After 6 hours, a plateau effect was observed, with little further decrease in NH_4-N concentrations or alkalinity. The trends were similar for wastewater from Sites 1 and 3, indicating that historical wastewater loading did not have a significant impact on the response to leachate loading for the wastewaters examined at the rates examined in this study. Young landfill leachate added at a volumetric loading ratio of 4% or above significantly increased NH_4-N concentrations compared with the control ($P<0.05$).

4.4 Discussion

4.4.1 Site 1

The leachate volumetric loading regime had no impact on WWTP performance and effluent concentrations at Site 1 over the study period. Site 1 struggled to meet NH_4-N emission limit values (ELVs) for all loading regimes (including no leachate). These results highlight the challenges faced in treating landfill leachate in WWTPs with low ELVs. Although co-treating leachate may not severely impact WWTP performance (i.e. removal efficiencies), it may not to be possible to achieve low ELVs, as the mass loading of the WWTP increases with increased leachate loading. There was no correlation between VLR_i and effluent NH_4-N concentration for Site 1. Observed final discharge NO_3-N concentrations indicate that nitrification occurred at Site 1 (Figure 4.1), although there were no significant differences between loading regimes.

4.4.2 Site 2

Changing leachate-loading regime at Site 2 from high to low shock loads increased NH_4-N removal efficiency and decreased effluent NH_4-N concentrations. Leachate co-treatment had an adverse impact on WWTP nitrification efficiency. At Site 2, final discharge NO_3-N concentrations were greater during the low leachate-loading period, possibly indicating the inhibition of ammonium-oxidising bacteria during the high leachate-loading period. There was a correlation between VLR_i and effluent NH_4-N concentration for Site 2 ($R^2=0.68$; $P<0.05$) but not for Site 1 (Figure 4.6).

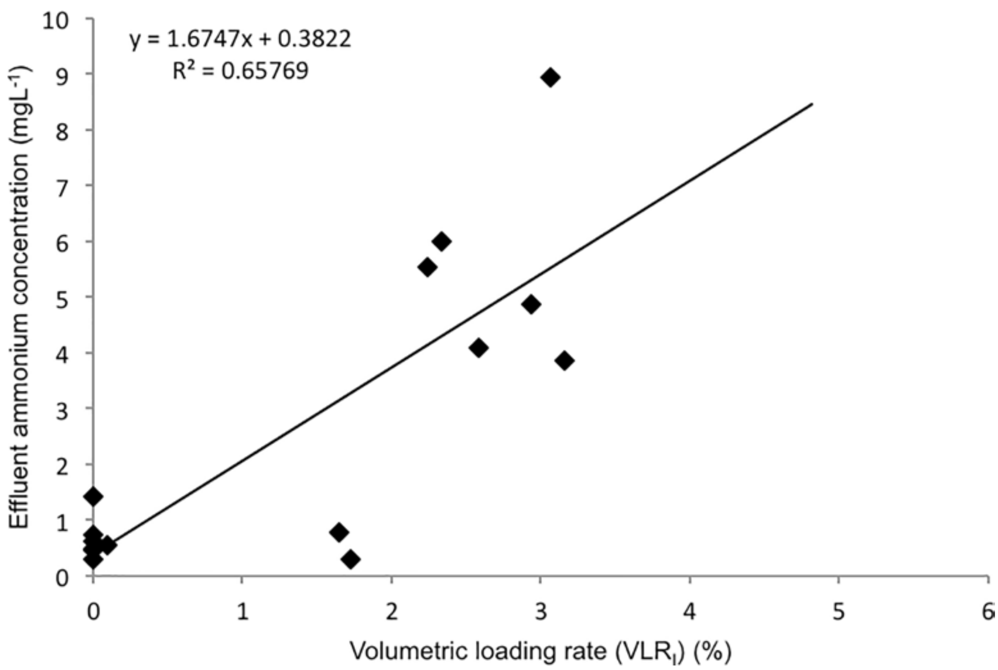

Figure 4.6. Relationship between WWTP VLR_i and effluent NH_4-N concentrations for Site 2.

4.4.3 Laboratory batch experiments

The results of the batch experiments were in agreement with site monitoring results and demonstrate that intermediate landfill leachate loaded at volumetric ratios of up to 4% or approximately 50% of total WWTP NH_4-N loading did not significantly inhibit nitrification processes (Figure 3.6). However, young landfill leachate, loaded at NH_4-N mass loading rates greater than 90% (equivalent to 2% VLR) of WWTP NH_4-N load resulted in a significant decrease in nitrification. Therefore, mass loading, not volumetric loading, must be considered when co-treating landfill leachate. These findings have significant implications for WWTPs accepting young landfill leachate similar to LL3 with high NH_4-N concentrations, as co-treatment at recommended VLRs may inhibit nitrification processes as seen here. When using a VLR of 4% (which corresponded to an initial concentration of approximately over 350 mg L^{-1} NH_4-N when LL3 was added to wastewater from Sites 1 and 3) nitrification was inhibited. It was not possible to determine an appropriate NH_4-N-based leachate-loading recommendation; however, loading rates of 2% (which in this study resulted in leachate NH_4-N accounting for approximately 90% of total WWTP NH_4-N load) or lower may be more appropriate for the young landfill leachate than the recommended 4% VLR. This could vary between leachates depending on NH_4-N concentration and the presence of other inhibitory compounds; these were not observed in levels likely to cause nitrification inhibition in this study (Table 4.5). The results of the beaker experiments were generally in agreement with results of current study site monitoring (Figure 3.4) and previous studies (Kalka, 2012: Ye *et al*., 2014). These results demonstrate that hydraulic-loading-based criteria alone may not be appropriate when co-treating leachate with municipal wastewater, unless leachate NH_4-N composition is considered and known in advance of acceptance. For the sites examined, the 4% rule is appropriate for intermediate landfill leachate but may not be appropriate for treating high-strength young landfill leachate that has not been pre-treated.

Addition of intermediate landfill leachate had no impact on final levels of alkalinity at $t = 48$ hours, although the addition of young landfill leachate significantly increased alkalinity compared with the control ($P < 0.05$) at all the rates examined. Alkalinity was observed to decrease steadily in all beakers, reaching a plateau at approximately 6 hours. This indicates most of the nitrification occurred within the first 6 hours of the batch experiments.

Effluent NO_3-N concentrations indicate that nitrification occurred in all beakers (Figure 3.5) with the exception of leachate from Site 1 co-treated with wastewater from Site 1 and young landfill leachate co-treated with wastewater from Sites 1 and 3 when added at a VLR of 10% ($P < 0.05$). It is likely that the relatively low alkalinity levels in the wastewater collected from Site 1 limited nitrification, because there was insufficient alkalinity to ensure that complete nitrification occurred [levels must be above 7.14 g alkalinity per g NH_4-N (Tchobanoglous *et al*., 2004)]. Inhibition of nitrification in the treatment of young landfill leachate (at a VLR of 10%) for both wastewaters was probably caused by leachate toxicity, as alkalinity was not depleted entirely.

Additional experiments were conducted to examine the use of aeration and coagulation as leachate pre-treatment technologies. These results are presented in Appendix 2. These results showed that pre-treatment of young landfill leachate using aeration significantly reduces NH_4-N concentrations compared with those in the untreated leachate. Coagulation did not have any impact on the initial NH_4-N concentration; however, NH_4-N concentrations following 48 hours of treatment were lower than untreated leachate ($P < 0.05$), indicating that coagulation in WWTPs could result in a decrease in NH_4-N concentrations. It was not possible to determine the cause of this relative improvement in ammonium removal when compared to untreated samples; however, it could indicate that NH_4-N toxicity alone was not the cause and perhaps treatment with $FeCl_3$ removed other nitrification-inhibiting compounds. These results demonstrate that pre-treatment technologies could be used to decrease the NH_4-N concentrations in leachate significantly either at the WWTP or landfill prior to co-treatment with municipal wastewater. In practice, site-specific nitrification trials should be conducted when accessing the potential impact of leachate acceptance, especially for young landfill leachate. It must be noted that the study of leachate pre-treatments was not extensive and did not examine the feasibility of using these treatments on site. If coagulation were to be used, the precipitate generated would have to be disposed of and this would have cost implications.

Figure 4.7 shows leachate COD and NH_4-N mass loads as a percentage of WWTP influent mass

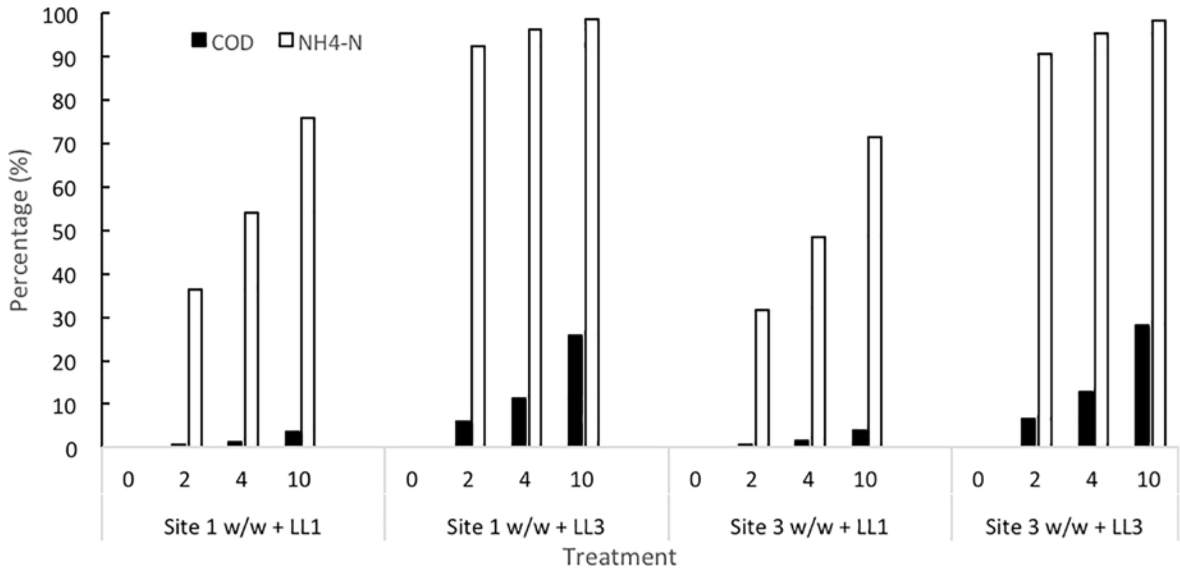

Figure 4.7. Leachate COD and NH_4-N mass loads plotted as a percentage of WWTP influent mass for laboratory batch experiments for volumetric loading rates of 0, 2, 4 and 10%.

for laboratory batch experiments plotted against percentage volumetric loading rate. These results show that, even for a VLR/VLR_i of 2%, which is half the recommended value, leachate NH_4-N can account for between 30% and 96% of NH_4-N in wastewater and leachate.

4.5. Conclusions

It should be noted that this report and its conclusions are based on a limited number of study sites. These results demonstrate the complexity of recommending appropriate management practices for the acceptance of landfill leachate by WWTPs. Although co-treatment of landfill leachate at WWTPs may be appropriate in some circumstances, the inherent variability in leachate composition and treatability necessitates a conservative approach. The main findings of this section are as follows:

1. Intermediate landfill leachate, loaded at NH_4-N mass loading rates of up to 50% (equivalent to 4% VLR) of total WWTP NH_4-N loading, did not significantly inhibit nitrification processes. Young landfill leachate, loaded at NH_4-N mass loading rates greater than 90% (equivalent to 2% VLR) of the influent WWTP NH_4-N load, resulted in a significant decrease in nitrification. Therefore, mass nitrogen loading, not volumetric loading, must be considered when co-treating landfill leachate.
2. The leachate-loading regimes (drip-feed and shock) examined were found to be appropriate for the effective treatment of intermediate landfill leachate in the WWTPs studied, but these results highlight the importance of NH_4-N and TN instantaneous loading rates when considering leachate acceptance at WWTPs. There may be a need for more stringent VLRs to be imposed.
3. Hydraulic-loading-based acceptance criteria recommendations alone may not be appropriate when co-treating young landfill leachate with municipal wastewater, unless leachate NH_4-N composition is considered and known in advance of acceptance. Site-specific batch experiments may be necessary to determine appropriate loading rates.
4. Results from batch experiments, presented in Appendix 2, showed that the pre-treatment of young landfill leachate using aeration has the potential to decrease the NH_4-N loading to WWTPs significantly and coagulation may potentially facilitate easier removal of NH_4-N in activated sludge processes. In reality, there are many practical considerations that would have to be addressed (i.e. odour, licensing) before aeration could be used on site.

5. Nitrogen loading should be considered when estimating the cost of leachate treatment, as leachate was found to account for up to 48% of TN and 32% of NH_4-N loading in the sites examined, accounting for a significant portion of WWTPs aeration requirements.

5 Cost Effectiveness of On-site and Off-site Treatment of Landfill Leachate

5.1 Introduction

Leachate treatment costs consist of operational and capital costs, and can vary significantly depending on leachate type and site-specific conditions (including age of landfill, strength of leachate, volume of leachate produced, standard of construction, rainfall intensity, availability of appropriate receiving waters and proximity to sewer/WWTP). In this analysis, the best available estimates derived from site visits to landfills and WWTPs, operator surveys, EPA reports and on-site monitoring were used to determine approximate treatment costs.

5.2 Materials and Methods

Following an initial survey of landfill and WWTP operators (described in Chapter 3), sites treating landfill leachate on site were identified. Data were collated from six landfills treating landfill leachate on site in Ireland. These landfills comprised five young landfills and one old landfill. Data from two pilot studies conducted in Irish landfills and laboratory trials, conducted in NUI Galway, were also collated. Data pertaining to landfill leachate treatment plant removal efficiency, effluent concentrations, volume of leachate treated and treatment costs (where available) were collated. Two sites in the process of commissioning on-site facilities also provided cost data, which was used to estimate the cost of existing facilities for which no cost data were available. Total annual operational costs and amortisation of capital costs were estimated and then converted to euros per cubic metre leachate treated for each landfill. The average marginal cost of leachate treatment in two WWTPs (Sites 1 and 2) were estimated by assigning additional personnel, monitoring, energy, chemicals and sludge removal costs incurred as a result of treating leachate (based on leachate volumes and WWTP influent volumes in 2013). The costs considered and assumptions used in the estimation of the average marginal cost of leachate treatment in the two municipal WWTPs examined are described in Table 5.1. The cost of off-site treatment was estimated using the best available estimates for leachate haulage costs and leachate gate fees. The landfill operators that provided information requested that all results included in the report be anonymised and, for this reason, the data presented in this section do not allow for the identification of the facilities that provided the information.

5.2.1 On-site leachate treatment

There are currently six on-site leachate treatment plants operating in Ireland, three of which discharge directly to surface water. Data collated from on-site leachate treatment plants demonstrated that leachate could be treated on site using SBR and RO systems (young landfill leachate) and CW for old landfill leachate. The level of treatment required is a function of leachate strength and whether or not the treated effluent is being discharged to sewer or to surface water. Sequence batch reactors decreased NH_4-N concentrations of between 128 and 1900 mg NH_4-N L^{-1} to between 0.3 and 2.8 mg NH_4-N L^{-1} for young landfill leachate. However, TN and COD effluent concentrations were too high for direct discharge to receiving waters. Reverse osmosis decreased NH_4-N concentrations from 2114 to 4.39 mg NH_4-N L^{-1} and CWs were proven to be effective at site scale and pilot scale for NH_4-N (Table 5.1). These results were in agreement with the results of a comprehensive review of leachate treatment options (Renou *et al*., 2008). Laboratory experiments conducted in NUI Galway showed that aeration of leachate was effective in reducing leachate NH_4-N levels for young landfill leachate but not for older landfill leachate. There may be potential to combine on-site treatment systems, such as RO/SBR and CW technologies, to produce higher-quality effluent that could be discharged on site where site conditions allow.

5.3 Results and Discussion

Capital costs estimated from information provided by operators varied from €260,000 for CWs to €500,000 for SBR systems, indicating that on-site treatment represents a significant investment and

Table 5.1. Costs considered and assumptions used in estimation of average marginal cost of leachate treatment in the two municipal WWTPs examined

Cost category		Assumptions
Personnel	Operative on site to receive leachate	Based on the estimated time a general operative would require on-site each week to receive leachate (WWTP operator survey follow-up questions)
	Management/administration	Based on the estimated time a senior engineer would require on-site each week to receive leachate (WWTP operator survey follow-up questions)
	Scientist	Based on the estimated time a scientist would require on site each week to receive leachate (WWTP operator survey follow-up questions)
Energy	Energy (excluding aeration and leachate pumping costs)	Energy meter data (SAFER data) obtained during monitoring period at Site 1 and Site 2 used to estimate annual energy usage assuming 0.14 €kw^{-1}
	Aeration	Mass loading analysis conducted assuming that 1.1 g of O_2 is required to oxidise 1 g COD and 4.72 g O_2 to oxidise 1 g NH_4-N; the energy used to aerate the WWTP was then assigned to leachate based on leachate NH_4-N and COD loading
	Leachate pumping	At Site 1, a dedicated energy meter was used during the on-site monitoring period to determine the energy used pumping leachate from storage tank to WWTP; this estimate was used to estimate annual energy usage
Other	Chemicals	Estimated based on chemical usage at each WWTP for 2014 and the cost assigned to leachate on a volumetric basis
	Sludge removal	Estimated based on sludge production during 2014 and the cost assigned to leachate on a volumetric basis
	Maintenance	Assumed based on WWTP operator survey follow-up questions and assigned on a volumetric basis
	Required toxicity analysis	Toxicity analysis required every 4 years at both sites and the cost distributed over 4 years

must be properly planned to ensure that the cost of its installation is recouped during its working life (Table 5.2). The estimated cost was observed to vary considerably between an estimated €1.30 m^{-3} for aeration (a simple pre-treatment) to €10.70 m^{-3} for RO and €22.90 m^{-3} for SBR treatment. Interestingly, RO represented the most cost-effective treatment in terms of NH_4-N removal at €5.10 kg^{-1} NH_4-N removed compared with SBR (ranging from €12 kg^{-1} NH_4-N removed to €183 kg^{-1} NH_4-N removed) and CW (€406 kg^{-1} NH_4-N removed). It is important to note that these costs can be skewed by relatively low NH_4-N concentrations and volumes. Clearly, the volume of leachate produced and the strength of leachate have significant impacts on leachate treatment costs and the cost per kg of contaminants removed; therefore designers must be cognisant of future treatment demands when investing in leachate treatment infrastructure.

5.3.1 Off-site leachate treatment

The majority of Irish landfills do not discharge leachate to local watercourses following treatment and the hydraulic requirement for transport is therefore a significant factor, irrespective of whether leachate treatment occurs at the landfill or at an off-site WWTP. The cost of leachate treatment can be divided broadly into treatment charges (also known as gate fees) and haulage costs. Respondents in the landfill operator/manager survey conducted as part of this project reported paying gate fees from no charge to €25 m^{-3}. Gates fees were typically based on volume (eight respondents), with two landfill mangers reporting an NH_4-N-loading-based pricing structure and one landfill manager reporting a COD- and BOD_5-loading pricing structure. There was no correlation between gate fees and leachate NH_4-N or COD concentrations. In addition, gate fees do not reflect the actual cost of leachate treatment and there was no correlation between treatment cost and NH_4-N or COD concentrations. Stakeholders expected that the establishment of a single utility company, Irish Water, responsible for water and wastewater services is likely to result in less variability in leachate treatment costs between WWTPs and bring an end to zero payments. Haulage costs were estimated to cost an average of €14.89 m^{-3}, based on data collated from landfill operators. This represents a large cost to landfill managers, as over 19,000 tankers (assuming 27 m^3

Table 5.2. Annual performance of on-site leachate treatment systems

Technology	Volume treated	Biochemical oxygen demand			Chemical oxygen demand			NH_4-N			Nitrate (NO_3-N)
	m^3	Inf ($mg\,L^{-1}$)	Eff ($mg\,L^{-1}$)	Effic (%)	Inf ($mg\,L^{-1}$)	Eff ($mg\,L^{-1}$)	Effic (%)	Inf ($mg\,L^{-1}$)	Eff ($mg\,L^{-1}$)	Effic (%)	Eff ($mg\,L^{-1}$)
Operational sites											
SBR	195	66	11	83	588	532	10	199	0.84	100	
SBR	17,355	488	49		3280	2226	32	1900	0.3	100	1788
SBR	21,074	205	5.58	97	1955			493	0.43	100	
SBR	20,984	66	16	76	651	263	60	128	2.8	98	149
RO	10,978	75	5	93	4780	7	100	2114	4.39	100	0.01
CW	6000	9	3	67	95	40	58	35.6	0.6	98	
Pilot studies											
CW	6132	20	3	85	279	145	48	323	3	99	
SBR		413	2	100	2438	564	77	1013[a]	0.25[a]	99[a]	
Aeration Site 1[b]					273	210	24	130	120	–8	
Aeration Site 3[b]					6150	6880	–12	2380	340	86	

The CW pilot study had duration of 7 years; the SBR pilot study had duration of 3 months and the aeration trials were 2-day beaker experiments.

[a]Effluent concentrations not provided by landfill operator, so the emission limit used as it is site is compliant and deemed a conservative estimate.

[b]The results of the pre-treatment study are described in Appendix 2.

Eff, effluent; effic, efficiency; inf, influent.

per tanker) of leachate transported an average of 70 km from landfill to WWTP in 2013. Using available data, a relationship was developed to estimate haulage costs (Table 5.3). The average marginal cost to the WWTP of leachate treatment was estimated to vary between €0.83 and €1.89 m^{-3} leachate treated, based on data collated from Sites 1 and 2 (see Table 4.7). These costs are between 1.4 and 8 times higher than the cost of wastewater treatment on a volumetric basis at these sites. These costs assume that WWTPs receiving leachate are compliant with water ELVs and that no capital works are required to accept leachate. Table 5.4 shows a cost comparison between on-site and off-site leachate treatment costs for selected landfill sites. These estimates show that the annual cost is lower for on-site treatment compared with off-site treatment for SBR and CW technologies. It must be noted that currently charging mechanisms do not fully reflect the cost of treatment and this comparison is limited in its applicability for that reason. These results show that haulage costs account for approximately 50% of the cost of treatment.

5.4 Implications for Landfill Managers

The selection of appropriate leachate treatment systems should be made based on site-specific conditions and sustainable systems should consider site-specific cost and compliance considerations (Stegmann *et al.*, 2005). This work aimed to provide information for landfill operators considering leachate treatment options. When considering leachate disposal, during site visits and operator surveys, several landfill managers highlighted outlet security and leachate disposal cost as the key reasons for developing on-site leachate capacity. This is particularly challenging for managers operating closed landfill sites. Although on-site treatment of leachate may be effective and is the preferred option for many landfill managers, on-site discharge is not always possible. In addition, it may be not be economically advantageous to treat leachate at the landfill unless WWTPs take leachate strength into account (i.e. introduce lower fees for weaker leachate). If a NH_4-N-loading-based tariff were to be introduced, then the economics of on-site treatment would change significantly.

5.5 Conclusions

The establishment of Irish Water is likely to accelerate the adoption of sustainable and cost-effective landfill leachate treatment, as a lack of certainty and consistency in the cost of leachate treatment in WWTPs has in the past discouraged investment in on-site treatment. The findings of this chapter are as follows:

1. On-site treatment of landfill leachate is effective. However, the economics of treatment vary considerably and are mainly determined by site-specific factors, such as proximity to WWTPs or suitable discharge points and the strength of the leachate.
2. Aeration trials conducted in NUI Galway show that on-site aeration of leachate may be an effective means of reducing leachate NH_4-N concentrations for young landfill leachate. This may mean that leachate could be transported to a nearer WWTP, which would reduce transport costs.
3. Introduction of a TN-loading-based tariff would have a significant impact on the economics of on-site leachate treatment.

Table 5.3. Estimated capital and operational costs for on-site leachate treatment systems in Ireland

Treatment	Volume treated (m^3)	Capital costs		Operational costs (maintenance, chemicals, energy and labour)		Cost of treatment per kg contaminant removed	
		Design, construction and commissioning costs (€)	Annualised cost (€ yr^{-1})[a]	Total operational cost 2014 (€)	Cost per m^3 treated (€)	NH_4-N (€ kg^{-1})	COD (€ kg^{-1})
SBR	17,355	500,000	50,926	345,711	22.9	12	21.7
SBR	20,984	400,000	50,926	430,172	22.9	183	59.1
RO[b]	10,978	400,000	40,741	76,846	10.7	5.1	2.20
CW	6,000	260,000	36,481	58,777	14.2	406	258
Aeration[c]	17,355	300,000	30,556	34,552	3.8	1.8	–

For the aeration pilot study, treatment costs were estimated for the landfill that provided leachate.

[a]Annualised capital costs were determined based on an 8% annual interest rate and a 20-year loan repayment period.

[b]RO generates permeate that is discharged to sewer and concentrate that is discharged into the waste mass. If this concentrate were to be treated off site, it would increase leachate treatment costs.

[c]Aeration costs for the old landfill leachate (Site 1) were excluded, as the treatment did not significantly reduce NH_4-N concentrations.

Table 5.4. Cost comparison between on-site (at landfill) and off-site leachate treatment costs for selected landfill sites

Technology	On-site treatment (€)[a]	Fate of leachate	Off-site treatment				Fate of leachate
			Haulage (€)[b]	Gate fee (€)[c]	Total off-site cost (€)	Annual costs (€ m^{-3})	
SBR	345,711	Sewer	178,768	193,842	372,610	–1.4	WWTP
SBR	430,172	Sewer	216,149	234,375	450,524	–1.5	WWTP
RO	76,846	Sewer	113,081	122,616	235,696	10.8	WWTP
CW	58,778	Surface water	61,804	67,015	128,819	–22.3	WWTP

[a]Calculated using estimated capital and operational costs for the existing treatment system during 2013.

[b]Haulage costs estimated using liner relationship ($R^2 = 0.54$) between cost of haulage and distance [cost = 0.0553 × (distance) + 6.4296] based on an average 70 km distance from landfill to receiving wastewater treatment plant and the volumes of leachate exported from each site in 2013.

[c]The average gate fee reported by landfill operators as part of the operator survey conducted in 2014.

6 Research Dissemination

6.1 Project Profile and Dissemination Activities

Dissemination activates have included face-to-face meetings with stakeholders, including local authority staff, researchers, landfill operators and WWTP operators. The project team have presented findings at national and international conferences and shared project progress and results using the project website (http://www.nuigalway.ie/leachate/), Slideshare (http://www.slideshare.net/RaymondBrennan/edit_my_uploads) and Twitter (https://twitter.com/LeachateNUIG). The email addresses of the stakeholders contacted as part of the project were compiled and two newsletters were sent (Appendix 3). These newsletters were also shared through Slideshare and have been viewed 362 times as of 14 March 2016.

In November 2015, the project team hosted an exhibition at the Irish Waste Management Conference 2015 (http://wasteconference.ie/), presenting results to industry professionals. The team also organised an end-of-project evening talk in conjunction with Engineers Ireland West Division at the National University of Ireland Galway (NUIG) on 8 February 2015, which attracted approximately 35 professionals working in the waste and wastewater sectors. This talk incorporated presentations from landfill managers regarding research and wastewater treatment scenarios (see the Engineers Ireland advertisement in Appendix 3).

6.2 Peer-reviewed Journal Papers

- Brennan, R.B., Healy, M.G., Morrison, L., Hynes, S., Norton, D. and Clifford E., 2015. Management of landfill leachate: the legacy of European Union Directives. *Waste Management* 55: 355–363. Available online: http://www.sciencedirect.com/science/article/pii/S0956053X15301598
- Brennan, R.B., Clifford, E., Devroedt, C., Morrison, L. and Healy. M.G., 2015. Treatment of landfill leachate in municipal wastewater treatment plants and impacts on effluent NH_4-N concentrations. *Journal of Environmental Management* (in review).

6.3 International Peer-reviewed Conference Presentations (Oral Presentations)

- Brennan, R.B., Healy, M.G. and Clifford, E., 2015. Impact of the Landfill Directive (1999/31/EC) on the concentrations, volumes and treatability of landfill leachate produced in Ireland. Presented at the 15th International Waste Management and Landfill Symposium Cagliari, Italy, 5–9 October 2015.
- Brennan, R.B., Clifford, E. and Healy, M.G., 2015. Impact of landfill leachate loading on the performance of three wastewater treatment plants. Presented at the 15th International Waste Management and Landfill Symposium Cagliari, Italy, 5–9 October 2015.

6.4 National Conference Presentations (Oral Presentations)

- Brennan, R.B., Healy, M.G., S Hynes, Norton, D. and Clifford, E., 2015. Optimisation of distance travelled by landfill leachate in Ireland. Presented at the GIS and Spatial Modelling in Research Seminar, Orbsen Seminar Room, Ryan Institute, NUIG, Galway, Ireland, 4 June 2015.
- Brennan, R.B., Healy, M.G., Morrison, L., Hynes, S., Norton, D. and Clifford, E., (2015). Impact of the Landfill Directive (1999/31/EC) on the concentrations, volumes and treatability of landfill leachate produced in Ireland. Presented at the 25th Environmental Science Association Ireland Colloquium, Sligo Institute of Technology, Ireland, 8–10 April 2015.

6.5 National Conference Presentations (Poster Presentations)

- Devroedt, C., Clifford, E., Healy, M.G. and Brennan, R.B., 2015. Influence of raw and pre-treated landfill leachate on nitrification processes in an activated sludge system. Presented at the Ryan Institute Research Day, 25 September 2015.

- Colin, B., Clifford, E., Hynes, S., Norton, D., Healy, M. and Brennan, R.B., 2015. Transport of landfill leachate in Ireland. Presented at the Ryan Institute Research Day, 25 September 2015.
- Brennan, R.B., Healy, M.G. and Clifford, E., 2015. Impact of landfill leachate loading on the performance of three wastewater treatment plants. Presented at the 25th Environmental Science Association Ireland Colloquium, Sligo Institute of Technology, Ireland, 8–10 April 2015.
- Brennan, R.B., Healy, M.G., Morrison, L., Hynes, S., Norton, D. and Clifford E., 2014. Suitability of municipal WWTPS for the treatment of landfill leachate in Ireland. Presented at the Environ Conference 2014, Trinity Collage Dublin, Co. Dublin, 26 February 2015.

7 Conclusions and Recommendations

7.1 Conclusions

Throughout the world, landfilling is in decline and landfill leachate has become a legacy problem. Unmanned landfill sites will require the development of sustainable leachate treatment options. These findings indicate that, although co-treatment of landfill leachate at WWTPs may be appropriate in some circumstances, the inherent variability in leachate composition and treatability necessitates a conservative approach. The conclusions of this study are as follows:

Leachate volumes and composition

- There is huge temporal and spatial heterogeneity in leachate strength, with young landfill leachate accounting for 42% of leachate volume per annum. Young landfill leachate accounts for over 70% of COD and BOD_5 load and 80% of NH_4-N leachate load in Ireland.
- The seasonal variation in leachate production poses a risk to effective co-treatment in municipal WWTPs, as periods of high leachate production coincide with periods of maximum hydraulic loading in WWTPs.
- Changes in landfill management, brought about by EU directives, have resulted in a decrease in the volume of leachate produced per tonne of waste sent to landfill and there is a trend towards increased leachate strength (particularly in COD and BOD_5 during the initial 5 years following landfill opening). However, this study did not demonstrate an impact of decreasing the relative volumes of BMW going to landfill on leachate composition.
- The implementation of EU directives has resulted in significant advances in landfill management and protection of the environment from the adverse effect of landfilling.

Co-treatment in municipal wastewater treatment plants

- The leachate-loading regimes examined here were found to be appropriate for the effective treatment of intermediate-age landfill leachate in the WWTPs examined, although co-treatment where low ELVs apply requires a well-managed and well-operated strategy for leachate acceptance.
- Hydraulic loading-based acceptance criteria recommendations are not appropriate when co-treating leachate with municipal wastewater, unless leachate TN composition is considered and known in advance of acceptance.
- Intermediate-age landfill leachate, loaded at NH_4-N mass loading rates of up to 50% (equivalent to 4% VLR) of total WWTP NH_4-N loading, did not significantly inhibit nitrification processes.
- Young landfill leachate, loaded at NH_4-N mass loading rates greater than 90% (equivalent to 2% VLR) of WWTP NH_4-N influent load, resulted in a significant decrease in nitrification. Therefore, mass loading – and not volumetric loading – must be considered when co-treating landfill leachate.
- When high-strength leachate is imported into a WWTP for the first time, laboratory batch experiments as described in Chapter 4, or similar, should be conducted before the leachate is imported to estimate the appropriate loading rates.
- Leachate pre-treatment technologies have the potential to significantly decrease the NH_4-N loading to WWTPs.
- Nitrogen loading should be considered when estimating the cost of leachate treatment, as leachate was found to account for up to 48% of TN and 32% of NH_4-N loading in the sites examined, accounting for a significant portion of WWTPs aeration requirements.
- Influent wastewater and leachate alkalinity should be considered when co-treating leachate to ensure sufficient alkalinity levels for nitrification processes to occur.

Cost effectiveness analysis

- Nitrogen loading-based tariffs should be implemented to allow landfill operators considering the installation of on-site leachate treatment systems to make economic predictions. This would provide the economic framework for sustainable development of leachate treatment infrastructure.

- On-site treatment of landfill leachate can be effective; however, the economics of on-site versus off-site treatment of landfill leachate vary considerably and are mainly determined by site-specific factors, such as proximity to a suitable discharge point or WWTP that can accept treated leachate.

7.2 Recommendations

Based on the conclusions of this report the following recommendations can be made:

- The current practice of co-treatment of landfill leachate at WWTPs is appropriate in most circumstances.
- Wastewater treatment plants and landfills should have overlapping measurement requirements for common contaminants. For example, TN is measured for WWTP influent, but leachate NH_4N is measured at the landfill. Measuring wastewater NH_4N and landfill leachate TN would allow for accurate TN and NH_4-N loading to be determined.
- When high-strength leachate is imported into a WWTP for the first time, laboratory batch experiments, similar to those described in Chapter 4, should be conducted before leachate is imported to estimate the appropriate loading rates.
- Nitrogen loading-based tariffs should be implemented to allow landfill operators considering the installation of on-site leachate treatment systems to make economic predictions. This would provide an economic framework for sustainable development of leachate treatment infrastructure.
- Leachate acceptance must be planned and provision must be made for the seasonal nature of leachate loading. In particular, leachate storage infrastructure at the landfill and WWTPs accepting leachate should be sufficient to minimise the risk of overloading WWTPs.
- Increased storage could be used as a buffer so that leachate could be added to the WWTP in a controlled manner. Wastewater treatment plants and landfills should design leachate storage facilities to allow for control of instantaneous leachate VLRs, as it is the loading rate over a short time period (i.e. over 24 hours), rather than the monthly/annual average that is of greatest concern to WWTP operators.
- Wastewater treatment plants considering leachate acceptance should take account of NH_4-N and alkalinity loading rates rather than VLRs. When completing annual environmental reports, WWTPs should include monthly breakdown of daily leachate volumes, loading regime (drip-feed or shock loading) and composition accepted for treatment.

8 Guidelines for WWTP operators

8.1 Guidelines for WWTPs Considering Leachate Acceptance

Wastewater treatment plant operators considering co-treatment of leachate should consider:

- developing leachate storage strategies in co-operation with landfill operator to avoid the risk of overloading WWTPs during periods of peak flow;
- provision of sufficient on-site storage to allow for the controlled discharge of the leachate over a 24-hour period;
- determining NH_4-N loading and designing leachate-loading regimes based on nitrogen loading and VLR; and
- conducting laboratory batch experiments, similar to those described in Chapter 4, when high-strength leachate is being imported to a WWTP to estimate appropriate loading rates.

8.2 Guidelines for Monitoring Impacts of Leachate Loading by WWTPs

When designing a monitoring strategy, operators must monitor the plant for a period before and after leachate is co-treated. Monitoring procedures should:

- Monitor the WWTP influent load for a period before and after leachate loading occurs to ensure that any change in plant performance is caused by leachate addition. In the current study, time periods of approximately 10 days were sufficient to observe the impact of leachate loading.
- Measure effluent alkalinity, NO_3-N, NH_4-N and TN using flow-weighted sampling methods to quantify the impacts of leachate loading.
- Take sufficient leachate samples during the monitoring period to ensure that leachate loading during the trial period is representative of expected loadings. The appropriate number of samples may vary depending on the degree of variability expected based on historical results and the hydraulic retention time of the leachate holding tank.

8.3 Guidelines for WWTPs in Estimating the Marginal Cost of Leachate Treatment

When considering the average marginal cost of leachate treatment, operators should examine the impacts of:

- introducing a NH_4-N loading tariff, rather than a volumetric-based tariff, to encourage landfill operators to reduce the NH_4-N loading on receiving WWTPs;
- using site-specific cost considerations and assumptions as outlined in this report (Table 5.1); and
- the cost of additional infrastructure required to ensure controlled release of leachate to WWTP when estimating costs of on-site treatment.

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Abbreviations

ANOVA	Analysis of variance
BMW	Biodegradable municipal waste
BOD_5	5-day biochemical oxygen demand
COD	Chemical oxygen demand
CW	Constructed wetland
DO	Dissolved oxygen
ELV	Emission limit value
EPA	Environmental Protection Agency
EU	European Union
MLSS	Mixed liquor suspended solids
MSW	Municipal solid waste
NH_4-N	Ammonium-nitrogen
NUIG	National University of Ireland Galway
PE	Population equivalent
RO	Reverse osmosis
SBR	Sequence batch reactor
SS	Suspended solid
TON	Total oxidised nitrogen
TN	Total nitrogen
VLR	Volumetric loading rate
VLR_i	Instantaneous volumetric loading rate
VSS	Volatile suspended solids
WWTP	Wastewater treatment plant

Appendix 1 Leachate and Wastewater Analysis Methodology

Parameter	Preparation	Methodology
TN	Unfiltered	BioTector analyser (BioTector, Cork)
Raw COD	Unfiltered	Lovibond COD test kits
Filtered COD	Filtered[a]	Lovibond COD test kits
BOD_5	Unfiltered	WTW OxiTop meters
NH_4-N, NO_3-N, NO_2-N, chloride, sulphate and alkalinity	Filtered[a]	Nutrient analyser (Thermo Clinical Labsystems, Aquachem 150)
Conductivity and pH	Unfiltered	Titralab 870
Cyanide	Unfiltered	Nutrient analyser (Thermo Clinical Labsystems, Aquachem 150)
Total metals (As, Ag, Cu, Cd, Cr, Fe, Pb, Ni and Zn)	Unfiltered samples digested using a CEM Discover SPD Microwave Digester using trace metal grade nitric acid (Fisher, UK)	Inductively Coupled Plasma Mass Spectrometry (ICP-MS) Shield Torch System (Agilent 7500a Technologies Inc., USA)

[a]Whatman GF/C; pore size: 1.2 µm.

Appendix 2 Leachate Pre-treatment Using Aeration and Ferric Chloride Coagulation Batch Experiments

Experiment Objectives

Additional laboratory batch experiments were conducted with LL1 and LL3 to examine two leachate pre-treatment technologies.

Methodology

For each leachate sample, four treatments were examined: (1) wastewater from Site 3 (control); (2) wastewater from Site 3 with raw landfill leachate added at a volumetric ratio of 4%; (3) leachate (LL1 and LL3) pre-treated using coagulation with ferric chloride (1 mg 8% $FeCl_3$ L^{-1}) followed by decanting; and (4) leachate pre-treated by 12 hours of aeration of leachate, each added to the wastewater at a volumetric ratio of 4%. Following pre-treatment of the samples, this experiment was conducted in the same manner as described in Appendix 1.

Results and Discussion

Aeration of the LL1 and LL3 samples decreased NH_4-N concentrations by 30% and 86% ($P < 0.05$), respectively, whereas coagulation had no impact on the leachate (Table 4.7). Aeration of the LL1 and LL3 samples decreased alkalinity, whereas coagulation had no impact. With the exception of NH_4-N concentrations and alkalinity levels, the leachate pre-treatments examined did not significantly impact leachate properties ($P < 0.05$). Figure A2.1 shows a photograph of the beaker experiment apparatus.

Figure A2.2 shows that pre-treatment of young landfill leachate using aeration significantly reduced NH_4-N concentrations compared with the untreated leachate. Coagulation did not have any impact on initial NH_4-N concentrations; however, NH_4-N concentrations after 48 hours were lower than untreated leachate ($P < 0.05$), indicating that the use of coagulation in WWTPs could result in a decrease in NH_4-N concentrations. It was not possible to determine the cause of this decrease in nitrification inhibition; however, this indicates that NH_4-N toxicity alone was not the cause and it is possible that the addition of $FeCl_3$ removed other nitrification inhibiting compounds.

Conclusion

These results indicate that pre-treatment technologies could be used to decrease the NH_4-N concentrations in leachate significantly at either the WWTP or landfill, prior to co-treatment with municipal wastewater. In practice, site-specific nitrification trials should be conducted when accessing the potential impact of

Figure A2.1. Photograph of batch experiment apparatus.

Table A2.1. Leachate and wastewater characteristics at the beginning of the leachate aeration beaker experiment immediately following pre-treatment.

Treatments		COD	NH_4-N	Alkalinity	TON	MLSS	VSS
Control	Activated sludge from Site 3	3652	8.76	86.2	0.32	3296	2660
LL1	Untreated (4%)	260	130	580	0.03	73.3	66.7
	Coagulation (4%)	60	127	480	0.02	40	20
	Aeration (4%)	210	80	390	6	40	30
LL2	Untreated (4%)	6150	2380	5562	0.01	367	293
	Coagulation (4%)	6140	2340	5541	0.05	250	190
	Aeration (4%)	6880	340	2280	0.1	270	205

All measurements are shown in mg L^{-1}.

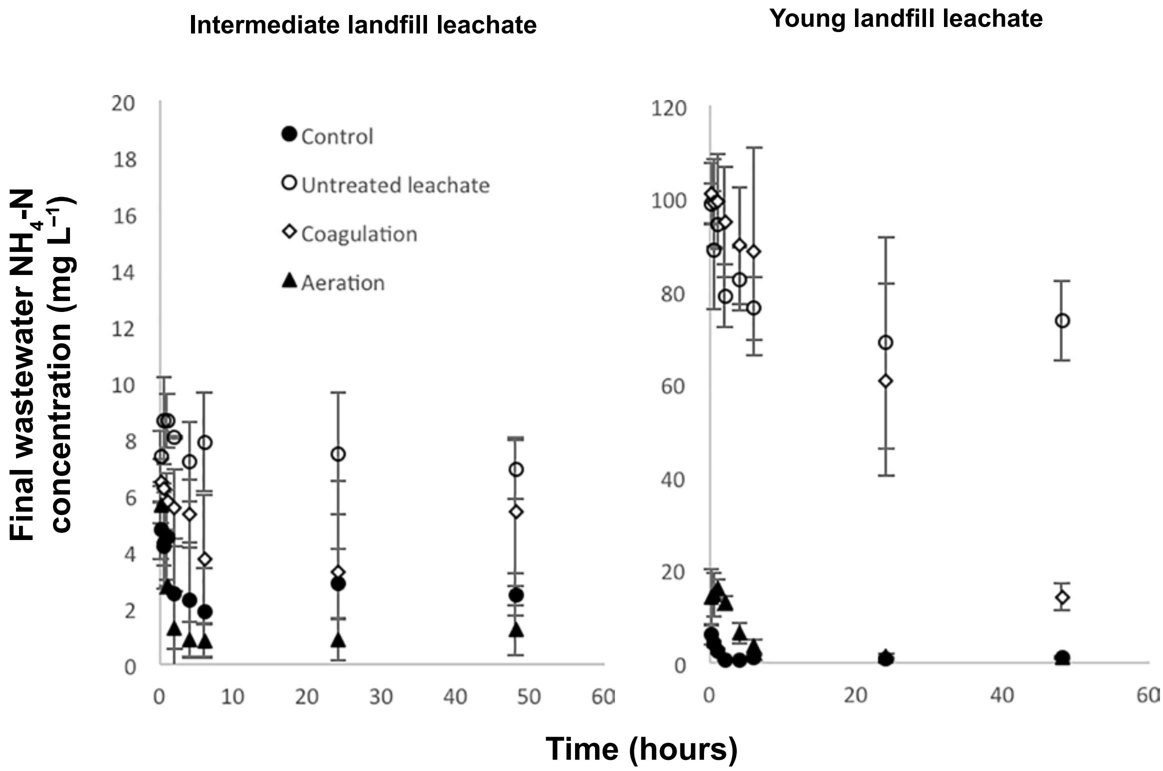

Figure A2.2. Wastewater from Site 3 amended with untreated leachate (4% volume) and leachate pre-treated with ferric chloride and aeration (error bars denote standard deviation).

leachate acceptance, especially for young landfill leachate.

It should be noted that this study of leachate pre-treatments was not extensive and did not examine the feasibility of using these treatments on site. If coagulation were to be used, the precipitate generated would have to be disposed of and this would have cost implications.

Appendix 3 Newsletters and the Engineers Ireland Advertisement

Newsletter 1

Treatment of landfill leachate by municipal wastewater treatment plants.

01/February/2015

Issue 1

Funding agency: EPA STRIVE Fellowship (No. 2013-W-FS-13).

Project duration: Dec. 2013—Dec. 2015

Website: http://www.nuigalway.ie/leachate/

Twitter: https://twitter.com/LeachateNUIG

Landfilling sequence of events:

1. Waste deposited in active cell.

2. Temporary Geohess liner which significantly reduces leachate generation while the landfill is settling.

3. Final capping which comprises impermeable LLDPE liner with subsoil and topsoil placed over.

(Photos 1,2 and 3 courtesy Westmeath CoCo)

Introduction

Internationally, there are on-going cases of groundwater and/or local environment pollution as a result of poor landfill leachate management. In Ireland 95% of municipal solid waste (MSW) landfill leachate (approximately 1.1 million cubic meters produced annually) is sent to municipal waste water treatment plants (MWWTPs) for final treatment. In recent years the Water Framework Directive has placed increasingly stringent water quality emission limits on MWWTPs resulting in increased costs associated with wastewater treatment. The establishment of Irish Water Ltd has increased pressure on all stakeholders to develop sustainable and cost effective leachate treatment practices. Landfills can generate leachate for over 30 years after waste ceases being deposited in the landfill and leachate management is set to be a problem in Ireland for many years to come.

In order to address this problem the project team are first characterizing the leachates and surveying landfill and MWWTP managers. Following this onsite trials are being conducted at MWWTPs to develop guidelines.

Project aims

As there is a need for research which provides the scientific, engineering, regulatory and policy stakeholders with clear evidence-based guidance on leachate management options, this project aims to develop guidelines for treatment of landfill leachate by:

1. Characterization of landfill leachate from open and closed sites.
2. Monitor the impacts of landfill leachate acceptance on MWWTP performance.
3. Evaluate the cost effectiveness on-site treatment versus off-site treatment of landfill leachate.

Project team

Raymond Brennan (Project Manager), Eoghan Clifford, Mark Healy, Liam Morrissey, Steve Hynes and Daniel Norton.

NUI Galway OÉ Gaillimh | STRIVE Programme | Ryan Institute

Contact: raymond.brennan@nuigalway.ie

Newsletter 2

EPA Research Code (2013-W-FS-13)

MANAGEMENT OF LANDFILL LEACHATE: THE LEGACY OF EUROPEAN UNION DIRECTIVES.

A synopsis of the key challenges facing waste and wastewater treatment professionals.

W nuigalway.ie/leachate/

@LeachateNUIG

Leachate project aims

- Examine the impact of EU Directives on landfill leachate management trends and composition.
- Determine the impact of leachate acceptance on wastewater treatment plant (WWTP) performance.

Leachate cycle

RAINFALL

\+

PERCOLATION THROUGH WASTE

=

LEACHATE

WWTP

DISCHARGE TO THE ENVIRONMENT

Data sources

- Landfill leachate characterisation study conducted at six Irish landfill sites (two operational and four closed landfills) by NUI Galway project team.
- Data collated from Annual Environmental Reports submitted by 48 landfills exporting leachate for treatment and 44 WWTPs treating leachate during 2013.

Management trends in Ireland

In the last 30 years, there have been significant improvements in **landfill design** and **construction standards**.

- Approx. **1.4 million m^3** of landfill leachate collected and treated annually.
- 94% of collected leachate treated in municipal WWTPs (50% of which was tankered to WWTPs during 2013).
- Landfilling of waste is on the **decline**.
- Landfill leachate is a **legacy problem** and leachate will require treatment for decades to come.
- General increase in the volume of leachate produced per tonne of waste landfilled.
- Trend towards increased leachate strength (particularly COD and BOD during the initial five years).
- Leachate contains **high ammonium-nitrogen (NH_4-N)** concentrations.

Engineers Ireland Advertisement

Term 2015 – 2016

ENGINEERS IRELAND
west

Engineers Ireland West

Landfill leachate in Ireland: A legacy problem.

Presented by: Raymond Brennan, Eoghan Clifford and Mark Healy (NUI Galway)

VENUE: Room G047, New Engineering Building, NUI Galway

DATE: Monday 8th February 2016

TIME: 7:00pm

The Lecture: Landfilling is in decline with European Union regulators targeting zero landfill by 2050. Unfortunately this does not spell the end to landfill leachate management concerns as leachate production continues for decades after the landfill has been closed. This lecture explores the history of landfill leachate management in Ireland and aims to address the key issues faced by landfill and wastewater treatment plant operators in Ireland. Its aims to provide a unique insight into landfill leachate management in Ireland with contributions from Irish Water, Tobin Consulting Engineers and NUIG researchers.

The Speakers:

Dr Raymond Brennan - Lead researcher/manager of the EPA funded STRIVE project entitled, 'Suitability of municipal WWTPs for the treatment of leachate from landfills in Ireland' at NUIG

Dr Eoghan Clifford Chartered Engineer - Lecturer in Civil Engineering, College of Engineering and Informatics, NUIG

Dr Mark Healy Chartered Engineer - Senior Lecturer, Civil Engineering, College of Engineering and Informatics, NUIG

Ciaran McGovern Chartered Engineer - Director Building and Infrastructure, Tobin Consulting Engineers Ciaran has management responsibility for Tobin's Building and Infrastructure division (Ireland and UK). He has extensive experience in the Waste Management sector including the construction, operation, aftercare and closure of landfill sites, together with the management of leachate during these project life cycles.

Dr Edmond O'Reilly Chartered Engineer - Wastewater Treatment Strategy Specialist, Irish Water. Working in Asset Strategy and Sustainability in Asset Management, Edmond has responsibility for the direction Irish Water takes in terms of wastewater treatment and the national investment requirements in this area. He is also Business Lead on the Wastewater Source Control and Licensing project established to define how Irish Water receives and manages wastewaters. His background is in wastewater treatment and technology development and he has completed BE (Civil), MEngSc and PhD (wastewater) degrees through NUI Galway.

Chairman	Dr. Gabriel Costello	B.E., Dip QA, M.Eng, Ph.D., CEng MIEI	GMIT	Tel: 091 742382	gabrielj.costello@gmit.ie
Vice-Chairman	Dr. Jamie Goggins	B.A. B.A.I. Ph.D CEng MICE MIEI	NUIG	Tel: 091 492609	jamie.goggins@nuigalway.ie
Hon Secretary	David O'Brien	B.A.I., B.A., PgDip(PM), MIEI	PMS	Tel: 091 877091	davidobrien@pms.ie
Hon Treasurer	James Mc Hale	BE, CEng MIEI	RPS	Tel: 091 400 200	james.mchale@gmail.com

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 214

Suitability of Municipal Wastewater Treatment Plants for the Treatment of Landfill Leachate

epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: Raymond B. Brennan, Mark G. Healy, Liam Morrison, Stephen Hynes, Daniel Norton and Eoghan Clifford

Identifying Pressures

In the last 30 years, there have been significant advances in waste and landfill management practices in response to European Union (EU) directives. These have led to changes in leachate composition, in the volumes of leachate produced and in its treatability. Furthermore, increasingly stringent wastewater discharge requirements mean that the co-treatment of leachate in municipal/urban wastewater treatment plants (UWWTPs) with other forms of wastewater can now be a challenge for some UWWTPs. Key challenges faced by UWWTP operators treating landfill leachate include high (i) ammonium-nitrogen concentrations in leachate and (ii) the increased cost of treating wastewater to increasingly stringent standards. It is anticipated that the requirement to meet these standards will drive UWWTP operators to consider their incoming load profile and the potential impacts on final standards that will be required. Meanwhile, increased costs, combined with concerns over leachate outlet security, are a significant challenge for landfill managers. In some cases, UWWTPs have ceased accepting leachate to comply with discharge licence requirements.

Informing Policy

The European Union (EU) Waste Management Act (1996), the Landfill Directive (1999/31/EC; EU, 2001a) and subsequent legislation have driven major changes in waste management in Ireland in the last 20 years, with the number of open municipal solid waste (MSW) landfills decreasing from 95 in 1995 to 4 in 2014 (EPA, 2014). However, leachate management is an area of growing concern for landfill and urban wastewater treatment plant (UWWTP) operators, as increasingly stringent water quality emission limits placed on UWWTPs by the Urban Wastewater Directive (91/271/EEC; EEC, 1991) and Water Framework Directive (2000/60/EC; EU, 2000) have resulted in increased costs associated with wastewater treatment. This report finds that although co-treatment of landfill leachate at UWWTPs may be appropriate in some circumstances, the inherent variability in leachate composition and treatability necessitates a conservative approach.

Developing Solutions

The study addressed a knowledge gap which existed regarding the suitability of UWWTPs for the treatment of landfill leachate. In addition the study examined the treatment of landfill leachate at landfill sites. Recommendations were made for wastewater treatment plants and landfills to have overlapping measurement requirements for common contaminants. The project developed a protocol for laboratory batch experiments, which can conducted before leachate is imported to a WWTP to estimate the appropriate loading rates. The study engaged with a wide range of stakeholders regarding leachate disposal routes and cost and recommended that nitrogen loading-based tariffs should be considered to give certainly to landfill operators considering the installation of on-site leachate treatment systems. This could provide a framework for sustainable development of leachate treatment infrastructure.

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